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PREFACE

This is Number 3 of Volume 47 of the Quarterly TRANSACTIONS of the A. I. E. E. It contains the one unpublished Winter Convention paper, together with those presented at the joint meeting of the New York Sections of the A. I. E. E. and the I. E. S., held in May 1928, and the papers and discussions of the St. Louis and Baltimore regional meetings.

The third Steinmetz Lecture, by Dr. Robert A. Millikan, is here published for the first time.

This number concludes with the Annual Report of the Board of Directors for the fiscal year ending April 30, 1928.

The last Quarterly each year will contain a complete topical and author's index for the four Quarterlies.

Spectroscopic Prediction

BY ROBERT A. MILLIKAN¹

Member, A. I. E. E.

NEVER in the history of science has a subject sprung so suddenly from a state of complete obscurity and unintelligibility to a condition of full illumination and predictability as has the field of spectroscopy since the year 1913.

It is my privilege today to recount the rapidly following steps in this spectacular advance which the Germans call *die Fortschritte der Spectroscopie*,—a peculiarly appropriate phrase since it is so beautifully descriptive of the step-by-step process by which theory and experiment interplay in rapidly bearing forward the body of our ever advancing knowledge.

I. THE BOHR THEORY

The great step which ushered in the new era was partly theoretical, partly experimental. It was taken when in 1913 Bohr² first thought of applying to the interpretation of spectra the then rapidly advancing idea that the frequency of a light-ray might be taken as a measure of the energy lost by its emitter or gained by its absorber—an idea first suggested by Planck³ in 1900; much more sharply formulated by Einstein, though still without adequate experimental warrant, in 1905⁴; definitely and quantitatively proved for photoelectric effects by a long series of experiments culminating in 1915⁵; and now the firm basis of the whole of modern spectroscopy. It is the most powerful instrument in spectroscopic prediction, and yet an idea which is completely at variance with all nineteenth century modes of thought, and thus far wholly irreconcilable with all the phenomena of interference which still find their interpretation only in terms of such a spreading-wave theory as denies any relation between frequency and energy. This relationship must be regarded simply as a new experimental fact holding in the domain of electronic phenomena, and of as yet unknown relationship to the large scale phenomena for the interpretation of which nineteenth century theories were developed.

And yet this great step of Bohr's, bold as it was, is after all a beautiful illustration of the conservative, step-by-step method by which physics has made most of its great advances. Instead of breaking away entirely from the past, as the foregoing comments may have indicated that he did, Bohr actually built con-

spicuously upon it. He incorporated the whole of celestial mechanics into the structure of his new atomic mechanics, merely adding to the old the features demanded by the newly discovered facts of radiation. Since the positive nucleus of the hydrogen atom attracts the negative electron in accordance with a law analogous to that which holds the earth to the sun, there was obviously no procedure consistent with the principle of minimum hypothesis, always followed by science, save to call upon the centrifugal forces engendered by orbital motion to prevent the attracting bodies, whether celestial or electronic, from rushing together under the influence of their mutual attractions.

But these hypothetical electronic orbits confront a condition not met with at all in the case of the equally hypothetical celestial orbits; for a planet or other celestial body has no mechanism for losing any appreciable fraction of its energy in a humanly speaking finite time, while in glowing hydrogen the atoms are continually interchanging considerable fractions of their energy with ether waves, sometimes absorbing and sometimes emitting such waves. The new experimentally discovered law of this interchange, *viz.*, $E_1 - E_2 = h\gamma$, in which the two E 's represent energy before and after emission, and γ the emitted frequency, h being constant, simply had to be added to the laws of celestial mechanics to obtain the laws of atomic mechanics.

This addition of the old theory and the new experimental facts constituted the essence of the Bohr theory. It was the old theory, *i. e.*, the laws of celestial mechanics, that required that when a hydrogen atom emitted radiation in accordance with the equation $E_1 - E_2 = h\gamma$, the electron drop into a new orbit of smaller radius, for in celestial mechanics the size of the orbit is fixed by the energy of the orbital system. The possible radii of the orbits of the electron of the hydrogen atom were thus limited to those whose energies differed by the observed emitted frequencies multiplied by the universal constant h , the dimensions of which were those of *moment of momentum*, and the observed emitted frequencies in hydrogen were such as to require that the possible orbits be limited to those for which the moment of momentum of the electron in its orbit progressed by unit steps, each an integral

multiple of h , or, more accurately, of $\frac{h}{2\pi}$.

Bohr thus put into his original picture three elements, the first theoretical, the last two experimental: 1, the laws of celestial mechanics, 2, the newly observed relation between frequency and energy, 3, the observed series of frequencies in the hydrogen spectrum. His boldness lay in two points; first, in that he postulated

1. Director, Norman Bridge Laboratory of Physics, Univ. of California, Pasadena, Calif.

2. Niels Bohr, *Phil. Mag.*, 26, 1, 1913; 26, 476, 1913; 26, 857, 1913.

3. Max Planck, "Wärmestrahlung," 1st Ed., 1900.

4. Einstein, *Ann. d. Physik*, 17, 132, 1905; 20, 199, 1906.

5. Millikan, *Phys. Rev.*, 7, 362, 1916.

Third Steinmetz Lecture, delivered before the Schenck Study Section on April 20, 1927.

non-radiating electronic orbits and thus denied the universal validity of Maxwell's equations; second, in that he ignored entirely, and purposely, the consideration of a *mechanism* of radiation. How an electron in jumping from one orbit to another of different energy can emit a radiation of frequency proportional to the energy-difference no one has as yet been able to suggest. Bohr simply set down and used the newly discovered experimental fact and forgot all about mechanism, a procedure which fifty years earlier had been so effectively used and so abundantly justified in the establishment and utilization of the second law of thermodynamics.

The original, simple theory of Bohr quickly had quite as remarkable quantitative successes as had had two hundred years earlier the corresponding orbital theory in celestial mechanics of Copernicus-Galileo-Newton. The latter not only furnished a satisfactory interpretation of the retrograde motions of the planets which it was devised to explain, but it made possible the prediction of the precise instant of eclipses, predictions which observations can now check with extraordinary precision, and therein lies its chief claim to modern acceptance.

Similarly, the Bohr theory not only furnished the first satisfactory interpretation of the hydrogen spectrum which gave it birth, but because of its orbital assumptions it enabled the Rydberg spectroscopic constant to be predicted from the accurately known values of the charge of the electron, its mass, and the value of h . *Purely spectroscopic observations check this computed value to within one-fourth of one per cent, and therein lay the first brilliant success of Bohr's orbital assumptions, though by no means their only one.*

The second and even more unambiguous success of Bohr's assumptions came three years later and constitutes what I shall call the second forward step in the process of spectroscopic illumination and prediction. It was an experimental step taken when Paschen made his very accurate measurement of the very slight difference in position, or wave length, of corresponding hydrogen and helium lines. This difference came out precisely as predicted from the four-fold difference in the masses of the central bodies about which the same sort of a body, a single negative electron, was supposed to be rotating in each case.

This altogether extraordinary and accurately quantitative check between prediction and experiment, constitutes perhaps as striking credentials for an orbital conception as has ever been met with anywhere in the history of orbital ideas, celestial or electronic. It seems quite uninterpretable save in terms of the conception of two widely different masses both of dimensions minute in comparison with their distance apart, revolving, just as the sun and the earth on the one hand, the nucleus and its electron on the other, are supposed to do about their common center of gravity.

II. RELATIVISTIC INTERPRETATION OF FINE STRUCTURE

The next important step in the advance of modern spectroscopy was taken when in 1916 Sommerfeld applied Einstein's relativistic considerations to the interpretation of the so-called fine structure of spectral lines, and in so doing brought still further powerful support to the theory of electronic orbits.

Bohr's simple theory had considered only circular orbits, the radius r of a given orbit remaining constant and the azimuth ϕ alone varying as the electron moved about in its orbit. In its inmost orbit the electron of the hydrogen atom had one unit of moment

of momentum, the unit being actually $\frac{h}{2\pi}$, in its sec-

ond orbit two units, in its third three, etc. This condition could be as well fulfilled with certain types of elliptical orbits as with circular orbits, but in that case two independent variables ϕ and r would have to be introduced to describe the motion in each ellipse. Sommerfeld applied the same sort of quantum conditions to both of these variables as Bohr had applied to ϕ alone before. He made the total moment of momentum⁶ of the system—the so-called total quantum number—the sum of an azimuthal and a radial quantum number, the way in which the total moment of momentum was divided between the two determining the ellipticity of the orbit. Thus, when the total quantum number was 1, the azimuthal quantum number had to be 1 and the radial quantum number 0, or else the azimuthal 0 and the radial 1. The first condition meant physically a circular orbit as in the simple Bohr theory, while the last meant a radial oscillation in which the electron had to pass through the nucleus, a physical impossibility. Hence the inmost orbit designated as a 1_1 orbit (the first integer denoting total, the last azimuthal quantum number, the radial being the difference between the two) had always to be a circle. For total quantum number 2, however, two different orbits were possible, namely, a 2_2 orbit, a circle (later designated a p orbit), or a 2_1 orbit, an ellipse (later called an s orbit) having its major axis equal to the diameter of the circle and twice its minor axis. The orbits of total quantum number 3 might have the shapes 3_3 , 3_2 , or 3_1 , as shown in Fig. 1, namely, a circle and two ellipses all having the same major axis but minor axes in the ratios 3, 2, 1.

So long as the Newtonian law of attraction governed the motions, all the orbits of a given total quantum number would have exactly the same energy (for this would be determined solely by the length of the major axis of the ellipse) and hence be spectroscopically indistinguishable since the only directly observable quantity in spectroscopy is the emitted frequency

6. More correctly "quantity of action" defined by $\int P_\phi d\phi + \int P_r dr$

determined by the electron jump from one orbit to another, *i. e.*, by the difference in the *energies* of two orbits. But when the Einstein relativity corrections are applied to the Newtonian laws there is introduced a change of mass with speed which makes the energy of binding of the electron to the nucleus in the case of a series of orbits of the same major axis (total quantum number) slightly greater the greater the ellipticity of the orbit, and hence makes the electron jumps into these orbits from a given position correspond to a number of slightly different frequencies, thus introducing fine structure into spectral lines. The theoretical procedure here adopted is in part the same as that used by Einstein in explaining the precession in the perihelion of mercury, *i. e.*, it is another instance of the application of the laws of celestial mechanics to the domain of atomic mechanics. The quantitative prediction of mercury's precession, however, involves the general relativity theory, whereas the foregoing has to do only with "special relativity."

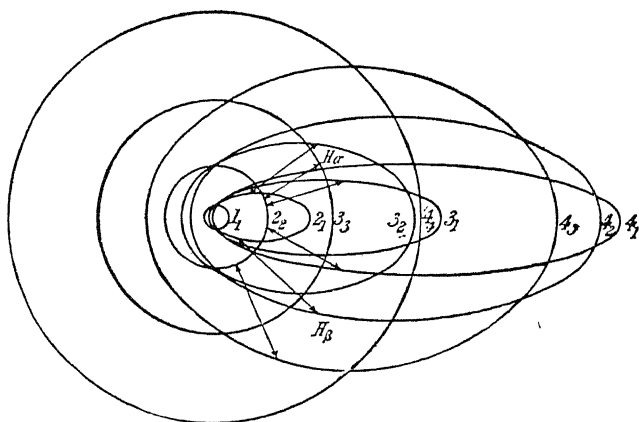


FIG. 1

This Sommerfeld relativistic interpretation of fine structure introduced new possibilities of spectroscopic prediction which from 1919 to 1924 had extraordinary successes. Thus, all the lines of the so-called Balmer series of hydrogen which consist of jumps into the state of total quantum number 2, a state possessing only two possible orbits, one a circle and one an ellipse, should reveal a fine structure corresponding to the difference in the energies of these particular circular and elliptical electronic orbits. To a first approximation they should actually all be doublet-lines with an accurately predictable difference in wave-length, or in frequency separation; and again *the prediction could be made wholly from the laws of orbital mechanics*. The theoretical value of the frequency separation of the hypothetical hydrogen doublets came out 0.365 cm.^{-1} frequency units. Now, with instruments of high resolving power, not only are these hydrogen lines *all* found actually to be doublets just as predicted, but the most accurate determination of this separation, obtained from H_β , recently made by Dr. William V. Houston in the

Norman Bridge Laboratory, comes out 0.36 cm.^{-1} —a value within a per cent of the computed value, an altogether outstanding and spectacular demonstration of the power of the physicist's newly discovered methods of spectroscopic prediction.

Again, the theoretical relativity formula made the frequency separation of a corresponding pair of lines vary with the fourth power of the atomic number so that the corresponding lines in ionized helium—like atomic hydrogen a simple nucleus-electron system but with a charge on the nucleus twice that in hydrogen—should be sixteen times as far separated as in hydrogen. This prediction also was accurately verified as early as 1916 by Paschen,⁷ his observed spectrum divided by 16 yielding, with extraordinary accuracy, 0.365 ± 0.0005 —another quantitative triumph of orbital theory.

Equally significant and even more beautiful as a piece of powerful analysis and wonderful prediction was Epstein's⁸ work on the effect of a superimposed electrical field in modifying electronic orbits of the foregoing sort, for he thus predicted correctly practically all the intricacies of the Stark effect—a triumph not only of the orbital theory but of the theoretical analysis itself.

But perhaps the most spectacular success of the relativity formula as applied to the interpretation of spectroscopic fine structure came when this formula predicted with approximate correctness the frequency separation of the so-called *L* doublets in the X-ray spectra of the heavy elements like uranium. Being a doublet corresponding, like the hydrogen doublets, to the electronic orbits of total quantum number 2, this ought (if it was actually a relativity doublet as assumed by Sommerfeld), to have a frequency separation obtainable by multiplying the observed separation in the case of hydrogen by the huge factor of 71 million, for this represents the fourth power of the ratio of the atomic number of uranium 92, to that of hydrogen 1. This prediction also checked with experiment.⁹

No theoretical formula in the history of physics has had more spectacular successes than Sommerfeld's relativity formula as applied to spectroscopic fine structure.

III. REGULAR AND IRREGULAR DOUBLET LAWS IN OPTICS

Another step that introduced new power into spectroscopic prediction was taken about 1920 in the development of high-vacuum "hot-spark" spectrometry¹⁰, for this enabled Dr. Bowen, Dr. Sawyer, and me not only to explore new regions of the ultraviolet spectrum and to add largely to our knowledge of spectra particularly in the case of the light elements, but also

7. Paschen, Bohr's Heliumlinien, *Ann. der Physik*, 50, 901, 1916.

8. P. Epstein, Zur Theorie des Stark Effekt, *Ann. der Physik*, 50, 489, 1916.

9. See Sommerfeld's "Atombau und Spectrallinien," 4th Ger. ed., p. 445.

10. Millikan, *Proc. Nat. Acad. Sci.*, 7, 289, 1921.

to develop new methods for the identification of lines and to discover new relationships that soon forced new interpretations and assisted in the introduction of fundamentally new conceptions into physics. Few more interesting instances of the exact verification of spectroscopic predictions can be found than are recorded in the work on stripped atoms.¹¹ Indeed, the discovery that our high potential vacuum sparks produced such atoms was made by predicting with the aid of the Bohr theory the exact positions and character of the lines to be expected from atoms stripped of all their valence electrons and hence reduced practically to hydrogen-like systems. It was only such reduction that at first made the predictions possible. The predicted lines were all found in the case of all the atoms of the first two rows of the periodic table except fluorine, which holds its electrons too tightly to enable our sparks to strip them all off. There were thus obtained for the first time in the field of optics the spectra of a long series of atoms of precisely like electronic structure but varying nuclear charge, namely, the series consisting of stripped Li, Be, B, C, N, O, and the second series consisting of stripped Na, Mg, Al, Si, P, S, Cl.

By the study of these series it was found that two laws found earlier in the field of X-rays and called the regular and irregular doublet laws held also in the field of optics, and they have since constituted powerful instruments for the prediction and identification of spectra. We have found them to be applicable to all series of like electronic structures, whether stripped or only partially stripped. The irregular doublet law enables one, if he can only get started on such a series, to predict the precise place in the spectrum, *i. e.*, the precise wave-length at which the corresponding lines of the other elements in the series are to be looked for, while the regular doublet law tells him the precise character of the line he should seek, *i. e.*, the frequency separations to be expected in its fine-structure. The foregoing is, then, a step in which the experimental foot goes forward. Next comes again the theoretical step.

IV. INNER QUANTUM NUMBER

The only cause of spectroscopic fine structure thus far considered has been the relativity cause which operates by virtue of a difference in the shapes of orbits of the same total quantum number. But it was found as early as 1920¹² that that was not enough to account for all the facts of fine structure. In X-rays, for example, the so-called *L* orbits or *L* levels correspond to a total quantum number 2, and this permits of only two different orbits, one a circle designated

as a 2_0 orbit, and one an ellipse designated as a 2_1 orbit; but X-ray absorption experiments brought to light three different levels or orbits, all close together in frequency, in which *L* electrons were actually found. Two of these followed the relativity law, also known as "the regular doublet" law referred to in the last paragraph. The frequency difference of these two levels varied with the fourth power of the atomic number, as demanded by the relativity equation. These two levels are represented by the two diverging lines marked L_{II} , L_{III} in Fig. 2. The third level, L_I , is seen to follow an entirely different law for it runs everywhere parallel to L_{II} . The frequency difference between L_I and L_{II} follows what was called the irregular doublet law in the last paragraph, so that the geometrical representation in Fig. 2 of the irregular doublet law is parallel lines, of the regular doublet law diverging lines. Similarly, in the field of optics there are found

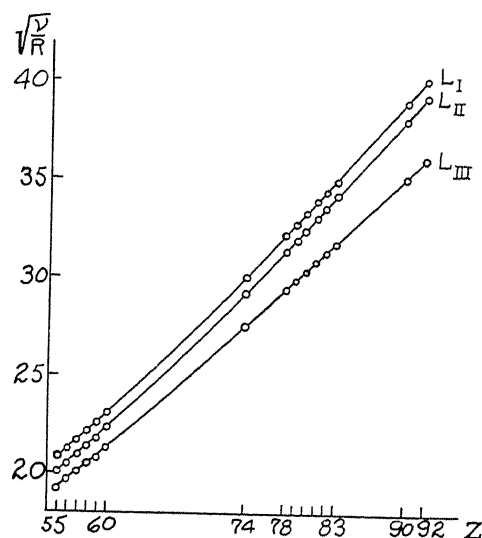


FIG. 2

experimentally three levels, or orbits, corresponding to the total quantum number 2, instead of merely the two permitted by the relativity theory. Since, then, only two different shapes were possible, Bohr and Sommerfeld introduced the idea that two orbits of the same shape, but of different orientations might exist, and that some dissymmetry in the central force-field gave these two orbits slightly different energies. They introduced a so-called inner quantum number generally denoted by the symbol *J* to take care of this variation in orientation, just as changes in azimuthal quantum number took care of variations in shape.

The difference in the frequencies of the familiar doublet lines in lithium, for example, was supposed to be due to the fact that these two lines represented jumps into a common orbit called an *s* orbit from two orbits which differed only in inner quantum number, *i. e.*, orbits of different orientations but the same shapes,—in this case circles, or $2, 2$ orbits, known as

11. Bowen and Millikan, *Proc. Nat. Acad. Sci.*, 10, 199, 1924; 11, 119, 1925; *Phys. Rev.*, 25, 295 and 591, 1925; 24, 209, 1924; 28, 923, 1926.

12. Sommerfeld, *Ann. der Physik* 63, 221, 1920. See also "Atombau und Spectrallinien," Chap. 8.

the $p_1 p_2$ orbits. The s orbit, on the other hand, into which these two electrons jumped to form the lithium doublet, was the third possible orbit of the total quantum state 2, namely, the 2_1 orbit of elliptical shape, the major axis being twice the minor. The two circular or p orbits differed only slightly in frequency or energy, but the change in energy in going from either of the p orbits to the s orbit was relatively very large, enormously larger than could be accounted for by the relativity effect introduced by change in shape alone. One of Bohr's most penetrating and important contributions to modern spectroscopy was made when in 1922¹³ he found a very simple orbital interpretation of this large difference in energy. Thus the elliptical, or 2_1 , orbit in hydrogen and helium differs only slightly in energy from the circular 2_2 orbit because, with a simple nucleus-electron system, there is nothing but the relativity cause to make a difference in energy, but in lithium, with its two close-in electrons in the K shell, and its one L electron in a much larger orbit of either circular form (2_2) or elliptical form (2_1) the case is quite different. For when this electron is in the 2_1 orbit, since the nucleus is at the focus of the ellipse, the electron must, at perihelion, dip inside the circular K orbits of the two K electrons, as it is shown in Fig. 1 to be doing, and there be relieved from the screening effect of these two electrons for it. In other words because of this *penetration of the elliptical orbit inside the K shell* the electron when in the 2_1 orbit gets into a field of force several times as intense as it would if it did not penetrate the K shell. It is thus, on the average, very much more tightly bound to the nucleus than is the electron in the 2_2 orbit which does not thus dip inside the K shell. Hence, wherever there is such an inner shell to penetrate, the energy difference between the 2_1 and the 2_2 orbits will be very much larger than the relativity difference. The very beautiful way in which this sort of explanation fits the observed facts whenever there are inner shells to penetrate constitutes another extraordinary triumph for the orbital conception. This Bohr mode of interpretation thus called on differences in *shape* with the consequent differences in interpenetration to account for the difference in energy between the p and s orbits, and left only differences in *orientation* with the same shapes, to account for the difference in energy between the p_1 and the p_2 orbits.

V. THE SPINNING ELECTRON

Now the extraordinary and disconcerting fact which Dr. Bowen and the author brought sharply to light as soon as we had obtained and hence could compare the spectra of a long series of stripped atoms like Li, Be, Bo, C, N, O, all of which had exactly the same electronic structure but varying nuclear charge, was that *the difference in energy between the two circular $p_1 p_2$*

orbits varied with atomic number in precisely the way demanded by the relativity equation.

There had been indications of this relation earlier. Sommerfeld in the first edition of his book, 1919, had suggested it but in later editions had discarded it as untenable because theoretically impossible and not experimentally justified. No unambiguous evidence could in fact be got until we had obtained a long series of atoms of identical electronic structures and varying nuclear charge to compare. We then found to our amazement, by careful quantitative studies, that *the energy difference between the $p_1 p_2$ orbits followed in every respect the relativity equation*, though it could not possibly be due to a relativity cause, since this cause required differences in shapes of orbits, while the $p_1 p_2$ orbits could not have differences in *shapes* but only differences in orientation.

In papers published in 1924 and 1925¹⁴ we therefore stated it as one of the most interesting problems of theoretical physics to retain relativity as a cause of fine structure in hydrogen and helium, and indeed in general, and yet to find another nonrelativistic cause "magnetic, or magnetic and electrostatic combined" which would follow exactly the relativity equation.

Probably never before in the history of physics had such an extraordinary—so well nigh impossible—a condition been imposed. And yet within a year of our statement of the problem, two young Dutch physicists, Uhlenbeck and Goudsmit¹⁵ stimulated partly by our work, partly by other difficulties with existing theory, pointed out especially by Landé and having to do with the so-called anomalous Zeeman effect, had found in the *assumption of the spinning electron* another cause of fine structure which followed exactly the same law in all respects as the relativity cause. The incident furnishes as striking an illustration as the history of physics thus far affords of the power of experimental and theoretical methods combined for predicting new phenomena, interpreting old ones and thus slowly but inevitably, step by step, forcing open nature's hitherto fast-bolted doors.

The new physical conception introduced by Uhlenbeck and Goudsmit is that every electron within an atom is not merely revolving in an orbit but at the same time rotating, just as does a planet, on its own axis. There are assumed to be but two possible directions of spin, 180 deg. apart, but the moment of momentum of spin is assumed to be always the same, namely, exactly one-half unit of moment of momentum

i. e., $\frac{1}{2} \frac{h}{2\pi}$. Such a conception introduces precisely

the right amount of energy difference between the $p_1 p_2$ circular orbits which is necessary to account for their observed spectroscopic frequency separation. This

13. N. Bohr, "Three Lectures on Atomic Physics," Vieweg Braunschweig 1922. Also *Ann. der Physik* 71, 228, 1923.

14. Bowen and Millikan, *Phys. Rev.* 24, 209-228, 1924; *Proc. Nat. Acad. Sci.* 11, 119, 1925; *Phil. Mag.* 49, 923, 1925.

15. Uhlenbeck and Goudsmit, *Nature* 117, 264, 1926.

effect is simply superposed upon the relativity effect, thus making the fine structure even in hydrogen and ionized helium somewhat more complex than could be accounted for by the relativity effect alone. *This newly predicted complexity has just been found by new and more refined measurements by Dr. Houston to fit the experimental facts much better than did the old theory.*

VI. THE NEW SPECTROSCOPIC RULES

With the aid of this new conception it has now become possible to make a nearer approach than heretofore to presenting a physical interpretation of a group of remarkable spectroscopic rules developed, largely empirically, within the past two years by Russell¹⁶, Heisenberg,¹⁷ Pauli,¹⁸ and Hund¹⁹ and embracing in an altogether remarkable way most of the facts of spectroscopy known up to the present. The success with which these empirical rules describe the facts of spectroscopy is little less than magical. These rules naturally all start with, and grow out of, the fundamental assumption underlying all quantum theory, namely, that all periodic motions must be quantized, *i. e.*, that periodic motion itself is unitary in its nature. As applied to atomic mechanics this means simply that all moments of momentum characteristic of the periodic motions within the atom are to be assigned characteristic quantum numbers and are to be allowed to change only by unit steps.

In the case of each individual electron there are just four sorts of such moments of momentum to consider. In other words there are four elements necessary to the complete description of an electron's motion within the atom, namely 1, the size of its orbit, 2, the shape of its orbit, 3, the orientation of its orbit in space, and 4, the orientation, or direction, of its spin. 1. The total moment of momentum (quantity of action, see p. 724) of an electronic orbit is characterized by its total quantum number n introduced by Bohr. This fixes the size (or major axis) of the orbit. 2. The azimuthal quantum number which, with a given n or major axis, fixes the shape (minor axis) of the orbit has heretofore been characterized by the quantum number k . For some reason not yet fully understood, but doubtless of profound physical significance (see below), in order to make the new spectroscopic rules fit the experimental facts it is found necessary to reduce by unity all values of k heretofore assigned. Since, however, we are not yet ready to discard entirely for the old purposes the old interpretations, this reduced value of k is for convenience denoted by a new symbol l , so that merely by definition $l = k - 1$. Thus for an s orbit $l = 0$, for a p orbit $l = 1$, for a d orbit $l = 2$ etc.

3. The projection of the orbital moment of momentum l upon any fixed direction of reference, which, in

the consideration of the Zeeman effect, is the direction of the applied external magnetic field, is quantized and designated by the symbol m_l . This projection obviously fixes the orientation of the orbit in space. The physical significance of the fact that this projection is quantized is that only certain definite orientations of this orbit are possible (such special quantization is directly proved by the so-called Stern and Gerlach experiments).

4. The projection of the moment of momentum of spin upon the fixed direction of reference is designated by the symbol m_s . As stated above, there are supposed to be in each atom but two possible directions of spin, 180 deg. apart; so that m_s of course determines in which of these two directions a given electron is spinning. The quantities m_l and m_s are usually called magnetic quantum numbers merely because of their use in connection with magnetic fields.

Now one of the new and very illuminating spectroscopic rules known as the Pauli exclusion rule states that in a given atom no two electrons may be alike in all four of the above elements; in other words two electrons cannot occupy one and the same electronic position within an atom.

This rule carries with it at once a whole group of conclusions which have been reached by piecing together evidence from many quarters. Thus it required that the K shell of all atoms possess two electrons and no more; for since in this shell $n = 1$ and $l = 0$ and hence $m = 0$ it follows from the rule that in the fourth element of their motion, namely the spin, the electrons must be different, and also that not more than two can exist without having two alike in all four elements and hence violating Pauli's rule.

Similarly, and for precisely the same reasons, there can be but two electrons in s orbits in a shell of any total quantum number whatever, and this in turn requires that the eight electrons of the L shell shall be found, two in s orbits and six in p orbits, a relation discovered by Stoner²⁰ and Main-Smith²¹ in England in 1924 by putting together evidence from a variety of sources.

Further, because of the opposite directions of spin of the two electrons of a K shell their joint or resultant moment of momentum and also their total magnetic moment must be zero, which in turn requires that helium be diamagnetic as it is found actually to be, in common with all the noble gases.

Pauli's rule also requires that every closed shell, indeed every completely symmetrical electronic configuration, have a zero value of its resultant moment of momentum, and also of its magnetic moment. This accords with the fact that mercury and other two-valence atoms, in their ground, or unexcited states, are diamagnetic.

16. Russell and Saunders, *Astrophys. Jr.* 61, 38, 1925.

17. Heisenberg, *Zeit. f. Phys.* 32, 841, 1925.

18. Pauli, *Zeit. f. Phys.* 31, 765, 1925.

19. Hund, *Zeit. f. Phys.* 33, 345, 1925.

20. Stoner, *Phil. Mag.* 48, 719, 1924.

21. Main-Smith, *Jour. Soc. Chem. Ind.* 44, 944, 1925.

Since every completed shell has zero moment of momentum it follows at once that the total or resultant moment of momentum of an atom having a given electronic configuration²²—and the number of different values that this moment can assume determines of course the number of terms in the fine structure corresponding to that configuration—must be made up of the combined moments of momentum of the electrons in the uncompleted or valence shell. This important relation was first perceived by Russell who also first formulated the new rules for the composition of the total moment of momentum of the atom from the foregoing components. Thus when more than one electron is present in the valence shell the joint orbital moment of momentum L of the whole group is obtained by taking the quantized vector sum of the individual moments l . For example, for two electrons in p orbits for each of which $l = 1$ the quantized vector sum is 0, 1, or 2. The physical significance of the fact that the vector sum of the l 's is quantized to obtain L is that the electrons are able to rotate only in orbits of such orientations about the nucleus that this vector sum is a whole number of units of moment of momentum. The next step is to obtain the joint moment of momentum R of the spins of the individual electrons. Since these spins are assumed to be in the same plane and

each of amount $r = \frac{1}{2}$, the quantized vector sum is

here simply the algebraic sum, *i. e.*, in this case

$$R = \frac{1}{2} - \frac{1}{2} = 0 \text{ or } \frac{1}{2} + \frac{1}{2} = 1.$$

Finally to obtain the total moment of momentum of the whole atom we take the quantized vector sum of the total orbital moment L and the total spin moment R . This is precisely the quantity which was originally called by Sommerfeld the inner quantum number and designated by the letter J . Thus for the values $L = 2$, $R = 1$, the quantized vector sum is 1, 2, or 3.

The fundamental quantum condition is now that all possible values of J constitute a series of which the successive steps differ by unity. If the value of R is an odd number of half units, *i. e.*, if there is an odd number of spinning electrons, then all the

values of J are obviously half integral ($\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$, etc.)

while if the value of R is integral, then all the values

of J are likewise integral. The number of possible values of J obtained from a given pair of values of R and L gives the multiplicity, *i. e.*, the number of terms in the fine structure. The maximum of the multiplicity is actually $2R + 1$.

The notation now in general use in the formulation of the new rules is as follows. When the value of L built up as above from the vectorial summation of the l 's of the individual orbits is 0, the term is by definition an S term. When $L = 1$ the term is by definition a P term; when $L = 2$ it is a D term; when $L = 3$ it is an F term, etc.

The foregoing quantization rules predict a much larger number of terms than are actually obtained from a given configuration, but Pauli's exclusion rule succeeds in reducing the number of terms to those actually observed.

The new rules thus briefly outlined have had such altogether extraordinary success in predicting the character of the spectra emitted, not only by the simpler atoms such as those which have been the subject of the studies of Dr. Bowen and myself, but by atoms like iron and titanium, thousands of whose lines have already been identified, that it seems as though we now have within our grasp the means of predicting the precise sorts of radiations which can be emitted by all the possible excited states into which any atom can be thrown. Indeed the predictions even of complicated spectra have recently been made so successfully that one prominent spectroscopist has lately remarked that "the heroic age of spectroscopy is already past."

Nevertheless these rules are still to a considerable extent empirical—a remarkable witness to the ingenuity of the physicist in picking out *rules of behavior*, and extrapolating by these rules from observed to unobserved phenomena. They are, however, little more than *rules*. They do not yet represent a logical and consistent scheme of interpretation, and they are only vaguely and very imperfectly translatable into physical pictures visualizable in terms of physical relationships. Thus, after the extraordinary and manifold successes detailed above which followed upon Sommerfeld's introduction of the idea of elliptical orbits—an idea definitely requiring that one unit of azimuthal moment of momentum be assigned to s orbits, two to p orbits, etc.—it is disconcerting in the extreme to find that to fit the new spectroscopic rules s electrons can have no orbital momentum at all ($l = 0$). This looks like a very fundamental contradiction and seems to spoil a whole group of interpretations which were thought to be quite definitely established. It is however just such contradictions which point the way to the next advance, as was so beautifully shown in the foregoing history of the development of the idea of the spinning electron. Furthermore this advance is perhaps already dimly in sight, for it has just been pointed out by Epstein that the new Schroedinger mechanics actually does

22. The word configuration as above used means the definite distribution or assignment of the valence electrons to their proper types of orbit, *e. g.*, $s^2 p^3$ means two electrons in s orbits and three in p orbits. Again $s^2 p^2 s$ means that one of the three p electrons, just referred to, has been pushed up into a higher state. Since there is a total of 6 p orbits, 3 electrons can be fitted into the 6 orbits in a considerable number of different ways and to each way corresponds a characteristic term value.

require that the s state (orbit) always represent a pure radial pulsation centrally symmetric, and without any axial structure, and hence without any angular momentum. The whole moment of momentum of electrons in the s state would then inhere in the spin. But just what influence this new group of idea is to have upon the whole group of orbital conceptions developed in the early portion of this review is still veiled in obscurity.

The last fourteen years of the history of spectroscopy, however, constitutes a remarkable illustration, first, of the rapidity of our modern rate of advance—a whole

huge domain, a veritable dark continent having been explored and reduced to order and civilization in a period of less than fifteen years; and second, of the power of the physicist's two tools, analysis and experiment, when used properly together, for forcing open nature's most tightly barred and bolted doors and wresting her most jealously guarded secrets from her for the enrichment of the life of future generations; for every bit of added knowledge of nature adds so much to our control over her, that is, to our ability to turn her hidden forces to useful ends.

Influence of Internal Vacua and Ionization on the Life of Paper Insulated High-Tension Cables

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Fellow, A. I. E. E.

and

LEO MASHKILEISON²

Associate, A. I. E. E.

Synopsis.—At the end of the year 1926 the High-Voltage Laboratory of the Electrotechnical Institute in Leningrad undertook an experimental research in order to study the influence of internal vacua and ionization on the life duration of paper insulated high-voltage cables, as well as to clear up the conditions under which such vacua may occur.

W. A. Del Mar³ drew attention to the importance of internal vacua in high-voltage cables and pointed out the three probable causes of their appearance, namely:

1. Temperature changes after installation of the cable, which produce a change of volume of air and oil in the cable in view of the different thermal expansion coefficient of lead and insulation of the cable.

2. Residual deformations, occurring when the cable is put on a reel and taken off it afterwards.

3. Changes in chemical structure in the impregnating compound under the influence of ionized air, which produce a decrease of volume of the compound.

The aim of the research was to clear up the part of the above mentioned causes in the formation of internal vacua, then to determine the values of those vacua and the decrease of life duration of the cable under the influence of the latter.

The research is not yet finished and only its preliminary results are reported on these pages.

* * * * *

OBJECT OF INVESTIGATION

AS an object of investigation a high-voltage cable was taken, the design of which is reproduced in Fig. 1.

The cable consists of three cores, each having a thickness of insulation of 10 mm. (25/64 in.) and each covered with a lead sheath. The three cores are wound together into a three-phase cable and are protected by a

conductors. The inner conductor serves for cable protection by the Lypro system.

The tests were made with single conductors of the cable having a length of 10 m. and with grounded lead sheath.

CONDITIONS OF TESTS

During the performance of tests chief attention was drawn: (1) to the control of internal vacua, (2) to the electric field design on the end of cables under tests, and (3) to the elimination of the cable end influence during loss measurements.

The ways of propagation of air in the cable were studied in order to work out the best method of control of the internal vacuum in the cable. For this purpose different methods of pumping the air out of the cable and of the manometer connections were tried. These tests showed that the propagation of air in the cable takes place chiefly along the stranded core in the inner part of it and immediately on its surface.

The insulation of the cable presents in most cases a medium quite impenetrable for air. Air can be concentrated in single bubbles between the insulation and the lead sheath, but it cannot propagate along the cable. In view of these facts the pumping out of the cable of air was made from one of its ends and the internal vacuum was controlled by two manometers connected with both ends of the cable.

In most cases the same pressure on both manometers connected with both ends of the cable was established during a few seconds. But in certain special cases obstacles were found in cables which prevented the longitudinal propagation of air.

As previously mentioned, the insulation of cables presents a medium quite impermeable for air. But in certain cases air may be propagated from the conducting core to the lead sheath by bifurcated paths between the sheets of paper strands of the insulation. This explains the leakage of air through the insulation of the cables'

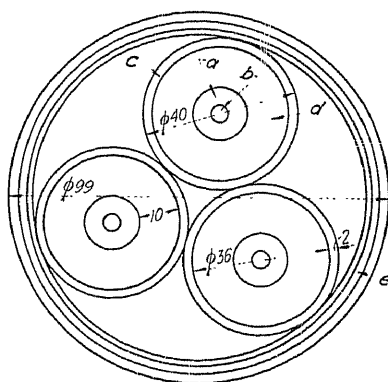


FIG. 1—CROSS-SECTION OF 35-KV. CABLE USED IN TESTS

- a. Outer copper conductor
- b. Inner conductor for Lypro cable protection
- c. Lead sheath
- d. Paper insulation
- e. Double steel ribbon armor

double steel ribbon armor. The working pressure of the cable is 35 kv. with grounded neutral and the working pressure for each phase is 20.2 kv. The conductor of each phase is split into two concentric stranded

1. Professor at the Electrotechnical Institute of Leningrad.
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3. William A. Del Mar, *The Effect of Internal Vacua Upon the Operation of High-Voltage Cables*. A. I. E. E. TRANS. 45, 1926, p. 572.

Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 19-17, 1928.

ends, for the performance of tests necessitated the taking off of the lead sheath on the ends of the cable on a length of 1 m. In some cases the leakage was so considerable as to make difficult the maintenance of a constant vacuum in the cable. The control of the electric field on the ends of the cable was accomplished

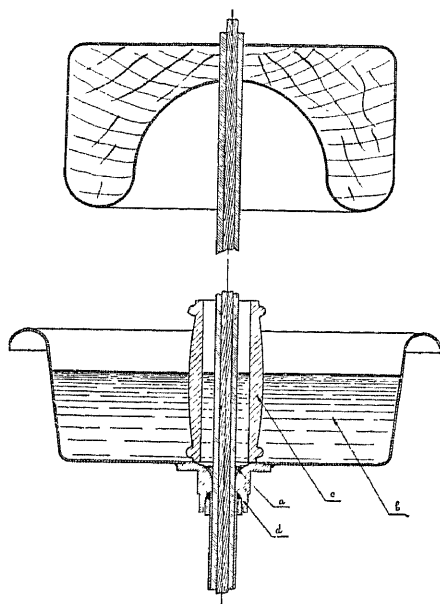


FIG. 2—CROSS-SECTION OF CABLE TERMINAL

- a. Hemp packing
- b. Transformer oil
- c. Porcelain bushing
- d. Stuffing box



FIG. 3—CABLE TERMINAL

by means of end insulation, schematically shown in Fig. 2 and on the photograph Fig. 3.

The upper electrode was made of wood and its surface was covered with tin-plate. The lower electrode is metallic.

On Fig. 2, *a* is a hemp packing, *b*, transformer oil, *c*, a porcelain bushing, and *d*, a stuffing-box. The test

of such a cable end insulator showed that its spark-over voltage is about 130 kv. This design of the cable end insulator provides quite a satisfactory form of the electric field on the ends of the cable, so that the breakdown of the cable during the tests occurred always somewhere in the middle of the cable, but not on its ends. If the curvature of the stuffing-box were made not along the arc of a circle, but along another more suitable curve, the spark-over voltage of such a cable end insulator could be noticeably increased without increase of its dimensions.

The elimination of the influence of cable ends on the measurement of losses in the cable was performed in the following way. At a certain distance from the ends of the cable two circular grooves 2 mm. wide were cut whereby the lead sheath was divided into three parts. The middle part was connected to Schering's

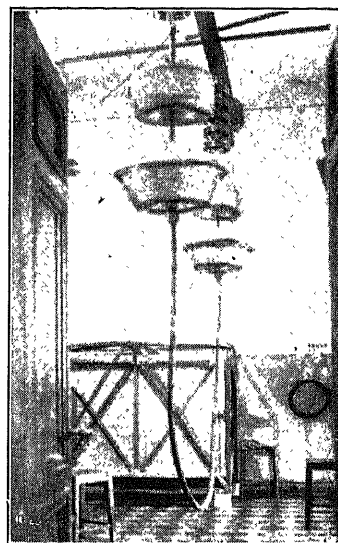


FIG. 4—CABLE READY FOR TEST

bridge for measuring the loss and the two outer parts were grounded and formed guard rings.

After the sample of the cable was prepared for the tests, the cable was hung on two strings of insulators, as shown in Fig. 4.

The test voltage was derived from three Koch & Sterzel transformers, 0.5/125 kv., which could be connected in series. The voltage control was effected by means of a potential regulator made by the same firm. The study of the voltage curve of the potential regulator showed that when the latter was fed from 500 volts, a sinusoidal curve was obtained with one transformer only for voltages above 47 kv. If the potential regulator was fed at 110 volts, its voltage curve proved to be sinusoidal also. Therefore, for voltages under 50 kv., the potential regulator was fed at 110 volts and three high-voltage transformers were put in series. For voltages above 50 kv. the potential regulator was fed at 500 volts and only one high-voltage transformer was used.

In all these cases, the voltage curve was of a good sinusoidal form, as indicated by oscillograms.

Dielectric loss measurement was made by means of a Schering bridge. The air standard condenser was of a flat type with three plates, the middle of which was connected to the high-voltage winding of the transformer. The working surface of the plates (without

tive resistance can be calculated as follows:

$$J^2 R_0 = E^2 \omega^2 C^2 R_0$$

This loss must equal the difference of losses measured in the two cases mentioned above. Agreement between the results of measurement and calculation indicates normal operation of the bridge. Such a proof of the bridge was made several times and always presented quite satisfactory results.

LIFE DURATION OF CABLE IN FUNCTION OF INTERNAL VACUA

For the determination of the life duration of the cable in function of internal vacua, different vacua

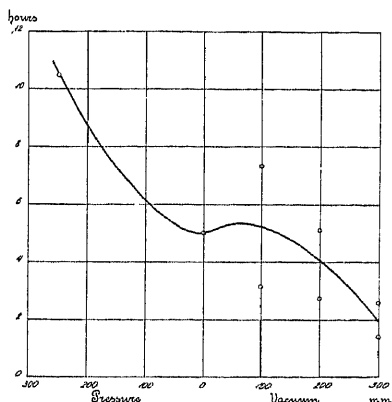


FIG. 5—VARIATION OF CABLE LIFE WITH PRESSURE AND VACUUM AT 60 KV.

guard rings) was equal to 17,840 cm.² The distance between the plates could be changed in such a way that even for very low voltages, about 3 kv., the power

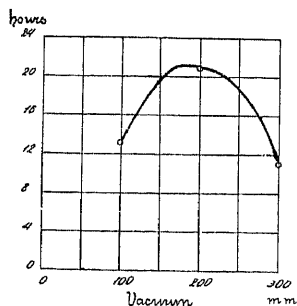


FIG. 6—VARIATION OF CABLE LIFE WITH VACUUM AT 50 KV.

factor could be accurately measured to three significant figures.

To clear up probable errors in the measurement of losses, phase displacements in the resistors were measured by means of a compensation method. This was also done with the parasitical capacities (capacity of the connecting conductor of the bridge and the capacity of the non-inductive resistances). These measurements showed that the largest probable error does not exceed a few seconds of phase displacement.

During the loss measurements the bridge was controlled in the following manner. After a measurement of the loss angle in the cable, a known non-inductive resistance R_0 was put in series with the latter and the loss angle was again determined. For a voltage E and a capacity C of the cable the loss in the non-induc-

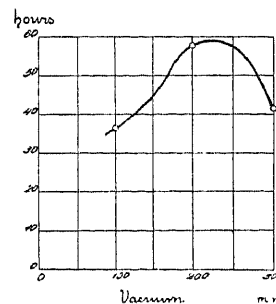


FIG. 7—VARIATION OF CABLE LIFE WITH VACUUM AT 42.6 KV.

were created in the interior of the cable and the latter was put under different voltages. During each test the vacuum and the voltage were held constant and the lapse of time was noticed, until breakdown of the cable occurred. As it was impossible to close the ends of the cable hermetically, as already pointed out, it proved

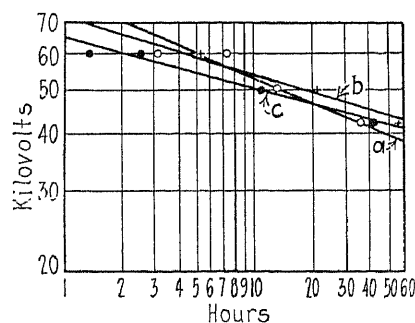


FIG. 8—VARIATION OF CABLE LIFE WITH VOLTAGES AT DIFFERENT VACUA

- a. 100 mm. vacuum
- b. 200 mm. vacuum
- c. 300 mm. vacuum

necessary to renew the vacuum periodically. This was done without taking off the voltage. The permitted variations of the vacuum were ± 5 mm. barometric pressure. But in several cases, when the leakage of air through the cable insulation was small, after the voltage was put on the cable, an increase and not a decrease of the vacuum was observed. This can probably be explained by chemical changes occurring in the impregnating compound under the influence of

ionized air and accompanied by a volume decrease of the compound, as suggested by item 3 of the synopsis.

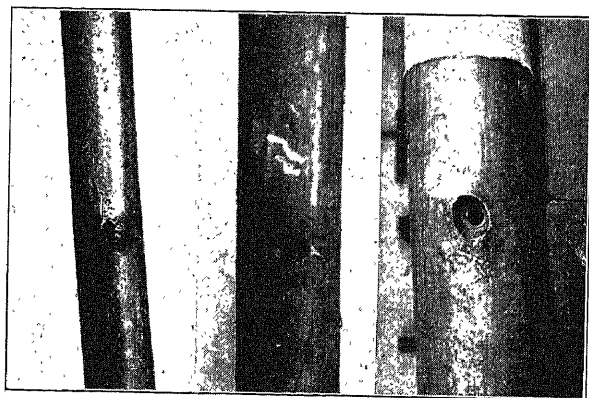
The chief results of tests of life duration of the cable under different vacua and voltages are given in Table I. On Figs. 5, 6, and 7 are drawn curves giving the life duration of the cable under different voltages in function of vacua, and the curves in Fig. 8 give the life duration under different vacua in function of the impressed voltage.

TABLE I

Voltage, kv. across 1 cm. of dielectric	Vacua in mm. of mercury column (under the atmospheric pressure)	Pressure in mm. of mercury column (over the atmospheric pressure)	Life duration in hours
60	..	250	10.5
60	0	0	5
60	100	..	5.2
60	200	..	4
60	300	..	2
50	100	..	13
50	200	..	21
50	300	..	11
42.6	100	..	36
42.6	200	..	57.7
42.6	300	..	41

The character of the places of breakdown of the cable is shown on Figs. 9, 10, and 11.

The study of curves on Figs. 5-8 shows the surprising



FIGS. 9, 10, 11—BREAKDOWN POINTS OF CABLE

fact that to each voltage corresponds a certain most advantageous vacuum, at which the life duration of a cable becomes a maximum, which is very sharply pronounced at voltages of 50 and 42.6 kv. and less sharply at a voltage of 60 kv. To check this fact, duplicate cables were tested and the results obtained showed a satisfactory agreement with the statement mentioned above. This would suggest the idea that this cannot be explained by lack of uniformity of the cable samples.

In addition to this it may be seen from the curves on Figs. 5-8 that the vacuum for which the life duration of the cable has its greatest value depends upon the voltage. With increase of voltage the maximum becomes smoother and is displaced in the direction of lower vacua.

DIELECTRIC LOSSES IN THE INSULATION OF THE CABLE IN FUNCTION OF THE INTERNAL VACUA IN THE LATTER

In order to make a more complete analysis of the influence of vacua on life duration of the cable and to clear up the phenomenon of an optimum vacuum, measurements of loss angles were made at different voltages and for different vacua and pressures in the interior of the cable. The results of these measurements are given in curves of Figs. 12 and 13 which show the losses as functions of internal vacua and pressures.

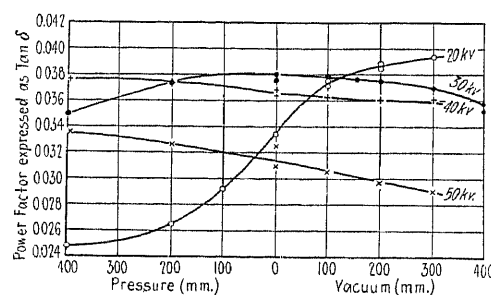


FIG. 12—RELATION BETWEEN POWER FACTOR AND INTERNAL PRESSURE

The vacua are drawn in the positive direction of the axis of abscissas and the pressures in the negative direction.

In Figs. 14 and 15 are drawn curves showing losses for different voltages as functions of different vacua and pressures. These losses are expressed as tangents of the imperfection angle δ of the dielectric. These are approximately equal to the cosines of the angle of lead for ordinary cable dielectrics such as those under consideration.

As we may see, with increase of voltage, $tg \delta$ in-

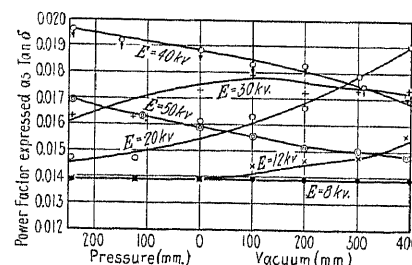


FIG. 13—RELATION BETWEEN POWER FACTOR AND INTERNAL PRESSURE

creases, reaches a maximum value, and then decreases. The maximum of $tg \delta$ is reached at a lower voltage as the internal vacuum becomes greater. The variation of the value of $tg \delta$ is least in proximity to the maximum.

An explanation of the decrease of power factor with increase of voltage was given by C. L. Dawes and P. L. Hoover.⁴ With an increase of voltage after all the air in the cable has been ionized, the potential

gradient in this air does not depend upon the voltage but equals the breakdown gradient of air. Hence it follows that the loss in air at any further increase of voltage will remain constant and the total loss in the cable will increase more slowly than in proportion to the square of voltage, *i. e.*, $t g \delta$ will decrease.

Assuming the loss angle of the dielectric proper (*i. e.*, without air) to have a constant value and neglect-

$$= E^2 \omega C \left[\left(\frac{E_0}{E} \right)^2 (t g \delta_0 - t g \delta_1) + t g \delta_1 \right] = E^2 \omega C t g \delta$$

Thus

$$t g \delta = \left(\frac{E_0}{E} \right)^2 (t g \delta_0 - t g \delta_1) + t g \delta_1$$

The curve drawn on Fig. 16 gives the loss in the cable as a function of the applied voltage at atmospheric pressure. The dotted curve gives the values of $t g \delta$, as calculated from the above formula. As may be seen, there is fairly good agreement between the calculated and experimental curves.

The curves on Figs. 12 and 13 show that a certain vacuum at which the loss is a maximum corresponds to each voltage. After the maximum is attained the loss begins to decrease and the velocity of decrease of the loss at first is greater then at a further increase of the internal vacuum.

With increase of voltage, the maximum loss is displaced in the direction of small vacua and consequently we find displaced in the same direction the

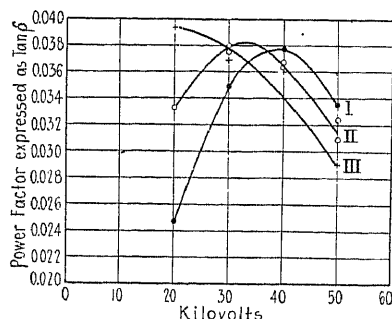


FIG. 14—RELATION BETWEEN POWER FACTOR AND INTERNAL PRESSURE

- I. Pressure 400 mm. over atmosphere
- II. Atmospheric pressure
- III. Vacuum 300 mm.

ing the small variations of capacity of the cable at increase of voltage, it is possible to determine the loss angle of the entire insulation (*i. e.*, including air) for voltages higher than the voltage E_0 , which corresponds

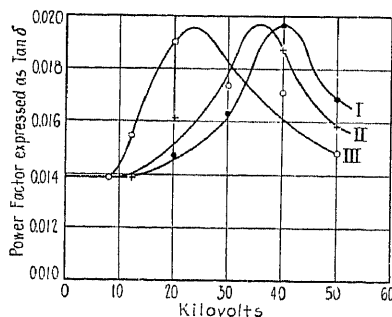


FIG. 15—RELATION BETWEEN POWER FACTOR AND VOLTAGE

- I. Pressure 250 mm. over atmosphere
- II. Atmospheric pressure
- III. Vacuum, 400 mm.

to the maximum value of $t g \delta = t g \delta_0$, if we know the loss angle of the insulation proper, $t g \delta$.

In effect the loss in air for a voltage $E > E_0$ may be expressed as follows:

$$P_1 = E_0^2 \omega C (t g \delta_0 - t g \delta_1) = \text{const.}$$

The loss in the insulation at a voltage E will be:

$$P_2 = E^2 \omega C t g \delta_1$$

Therefore the total loss will be equal to:

$$P = P_1 + P_2$$

4. C. L. Dawes and P. L. Hoover, *Ionization Studies in Paper Insulated Cables*, A. I. E. E. TRANS., Vol. 45, 1926, p. 141.

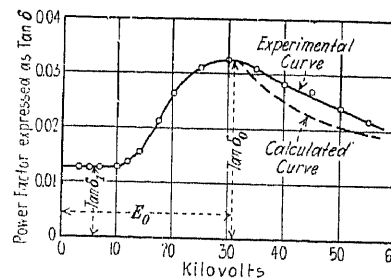


FIG. 16—COMPARISON OF CALCULATED AND EXPERIMENTAL CURVES BETWEEN POWER FACTOR AND VOLTAGE ABOVE THE VOLTAGE OF MAXIMUM POWER FACTOR

parts of curves with diminished loss variations. Thus we have a relation of the same character as that already mentioned, between the life of the cable and the internal vacua. This similarity shows that there is something in common between the two phenomena and suggests the ways for explanation of the nature of the phenomenon of the optimum life vacuum.

A complete explanation of this phenomenon was not yet found, but it is possible that its cause may be as follows.

With an increase of the internal vacuum in the cable at a constant voltage, (beginning from large pressures of the internal air at which the air is not yet wholly ionized), the loss will increase at first. Then with a vacuum, at which the internal air is wholly ionized, the loss will attain its maximum value. With a further increase of the internal vacuum the loss will decrease, as the dielectric strength of air will decrease and therefore the voltage drop across the air will also decrease. As the dielectric loss will heat the cable, the temperature

of the latter will vary approximately in the same manner as its dielectric loss.

As the life duration of a cable must naturally decrease with an increase of hot-spot temperature, it should at first decrease with an increase of the vacuum, and then increase. With increase of the vacuum, however, because of the decrease of voltage drop through the air, the gradient of the electric field in the insulation of the cable must increase. In the same way, the tangential components of the gradient along the joints of paper strips of insulation must also increase. All these causes provoke a continual decrease of the life duration of a cable with increase of the vacuum. For instance the fact that the life duration becomes five times less, at a voltage of 60 kv. with a change of conditions of the internal air in the cable from a pressure of 250 mm. (over atmospheric pressure) to a vacuum of 300 mm., suggests that in general the dielectric strength of a solid insulation may depend upon the pressure of the surrounding air. In a cable it is quite possible that the barrier or baffle properties of the insulating paper become inferior and a freer motion of ions begins in the latter.

Thus we see that with an increase of vacuum, at first all causes tend to provoke a decrease in the life of the cable. Then, when the loss and consequently the temperature begin to decrease, their influence may

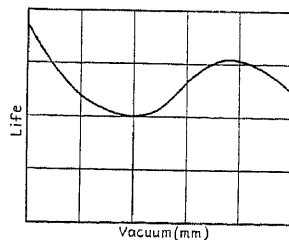


FIG. 17—TYPICAL LIFE-VACUUM CURVE AS SUGGESTED BY POWER FACTOR AND VACUUM RELATION

become predominant in comparison with all other causes and the cable's life will begin to increase. With a further increase of vacuum, the rate of variation of losses, as stated above, will diminish. This will lead to a state when the influence of causes decreasing the cable's life will predominate.

This analysis shows that the curve giving the influence of the vacuum on a cable's life duration must be of s shape shown in Fig. 17. This curve has the same shape as that obtained by experiment for a voltage of 60 kv. and reproduced in Fig. 5. For the other two experimental curves drawn on Figs. 6 and 7, we have only the parts containing the maximum, as these were not determined over a wide range of pressures. The fact that the maximum becomes smoother with an increase of voltage can be explained in the following way; at high voltages, the gradient in the insulation of the cable and the tangential components of the

gradient become of prevailing importance, for, at high voltages, when the air is wholly ionized, the losses decrease with an increase of vacuum and the influence of their decrease at an increase of the vacuum becomes less perceptible.

At the working voltage of the cable, the optimum vacuum as it appears will be so considerable that it will be practically necessary to take into consideration only the decrease of the cable's life.

THE APPEARANCE OF INTERNAL VACUA IN CABLE IN CONSEQUENCE OF CHEMICAL AND THERMAL ALTERATIONS

It has been mentioned that during the tests for determining the life duration of the cable in function of internal vacua, a tendency to an automatic increase

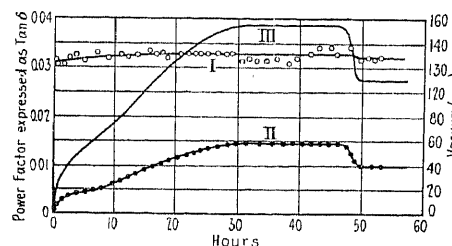


FIG. 18—CHANGE OF VACUUM AND POWER FACTOR AS RESULT OF PROLONGED LIFE TEST

- I. Power factor
- II. Observed vacua
- III. Vacua corrected for parasitical volumes

of the vacuum was observed, as it seems under the influence of chemical alterations in the impregnating compound under the influence of ionized air.

To study this phenomenon quantitatively, a piece of cable was put under atmospheric pressure of air on its working voltage of 20.2 kv. A manometer was connected to one of the extremities of the cable to observe the appearance of the internal vacua. The other extremity of the cable was hermetically closed. At the same time, loss measurements were undertaken. The curves in Fig. 18 reproduce the results of the experiment. The curves are: I, the loss curve; II, the curve of observed vacua; and III, the curve of vacua, which would happen if there would not be connected to the cable the parasitical volume of air in the leads of rubber tubes and in the manometer.

The sudden decrease of vacuum at the end of the experiment can be explained by imperfect sealing of the cable.

The volume of air, which it was necessary to know to plot curve III, was measured by applying to the interior of the cable, a known volume of air at atmospheric pressure and observing the change of the vacuum after its introduction into the cable.

It is obvious from curve III that under the working voltage of the cable, vacua approximating 155 mm. of mercury may appear.

For the determination of internal vacua which can appear under the influence of temperature changes, a piece of cable was heated to a temperature about 40 deg. cent., measured by a thermometer dropped to the core of the cable.

The cable was heated with an electric current about 800 amperes. After the heating current was interrupted, in a lapse of time, which allowed to attain a comparatively uniform distribution of temperatures in the

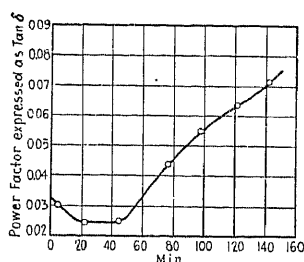


FIG. 19—RELATION BETWEEN POWER FACTOR AND LIFE ON A CABLE WHICH FAILED IN 157 MIN.

interior of the cable, the latter was hermetically closed and connected to a manometer.

In this way it was found that at a decrease of temperature in the cable of 25 deg. cent. the internal vacuum increased to 180 mm. of mercury (corrected for the parasitical volume in leads of rubber tubes and the manometer).

LOSSES IN CABLE AS FUNCTION OF THE DURATION OF VOLTAGE APPLICATION

Loss measurements in the cable were made at the same time as life duration of the cable as a function of the internal vacua was determined.

Characteristic curves of power factor as function of applied voltage obtained during these tests are reproduced in Figs. 19 and 20. As may be seen from these curves, $tg\delta$ at first diminishes, then remains constant for a time, and then increases until breakdown of the cable occurs.

The decrease of $tg\delta$ during a certain time after the application of voltage may be explained by the heating of the cable through the dielectric losses. The ambient temperature was about 15 deg. cent. and as the cable losses have a minimum at a temperature about 40 deg. cent., as shown by Mr. P. Dunsheath,⁵ the heating of the cable leads to a decrease of $tg\delta$. After establishing a thermal equilibrium, $tg\delta$ remains constant for a certain period. This shows that the chief causes of the breakdown in the cable are chemical alterations, not pyroelectric effects.

If breakdown in the cable were due to thermal causes, we should have a continual rise of temperature in the cable and the loss curve would not have its horizontal part. The pyroelectric effect begins to play an im-

portant part only at the approach of the cable's breakdown, which accounts for the appearance of hot spots before the breakdown.

CONCLUSIONS

1. Internal vacua of the order of 350-400 mm. of mercury may appear in a cable under the influence of temperature changes and ionization of air.

2. The appearance of internal vacua at the working voltage of a cable may noticeably lower the life duration of the latter.

3. Air can easily propagate along the core of a cable and in the interior of the latter, but on considerable lengths of cable stoppers may occur, which will impede such a propagation.

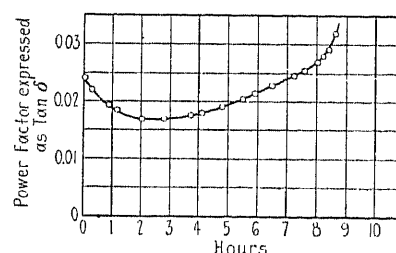


FIG. 20—RELATION BETWEEN POWER FACTOR AND LIFE ON A CABLE WHICH FAILED IN 10 HR. 29 MIN.

4. To prevent the dangerous effect of internal vacua the following measures may be recommended:

- a. Use of chemically stable compounds;
- b. Arrangement of free ducts in the interior of the cable for air to maintain the atmospheric pressure in the interior of the cable by using the flow of air from the extremities of the cable;
- c. Arrangement of free air ducts in the interior of the cable and in the splices for compensation of vacua that may appear with the volume of air contained in them;
- d. Pumping of dry air through ducts in the core of a cable to maintain the pressure in the cable higher than that of the atmosphere;
- e. Filling a cable with transformer oil forced under pressure at the splices of a cable to provide compensation at volume changes of internal air in the cable.

Discussion

W. A. Del Mar: This paper has been very interesting to me because we tried in the laboratory of the company with which I am connected to do this work several years ago, and encountered very serious experimental difficulties. We found great difficulty in maintaining the vacua at the ends of the cable without weakening the terminals, so that the terminals, rather than the cable, would fail. We made a great many break-down tests, but none of the results ever reached the point where we could bring them before the Institute for discussion. Yet there was a very definite indication that there was a connection between the internal pressure of the cable and the life. For instance, five cables were tested with a vacuum of about 24 in., and the average life of those cables was 20 hr. Similar cables were tested at the same voltage at atmospheric pressure and the aver-

5. P. Dunsheath, "Dielectric Problems in High-Voltage Cables," *Journal of the Institution of Electrical Engineers*, January, 1926.

age life was 274 hr. When we came to analyze these individual results there was not a single one that was really conclusive. Something happened in every test, either the vacuum line became clogged, or we were not sure that the pressure was the same at the two ends of the cable, or else the terminals failed. We made repetitions of these tests and ran into similar difficulties, and by the time we had just about reached the point where we believed we had solved the terminal problem we were obliged to stop the work and go on to something that was then more important. It was therefore very gratifying to see these Russian experimenters take up the work.

Since the presentation of my paper in 1926 on *Vacua in Cables*, a number of pertinent observations and tests has been made, but more problems have been raised than solved.

The application of reservoirs of oil to cable joints to compensate for pressure changes due to expansion and contraction of cable compound has become standard practise for voltages above 20,000, but certain observations to date suggest that cable may have an unexpectedly large capacity for absorbing oil from the reservoirs. The questions naturally arise—how long will this appetite last and where is the oil going? Observations, theory, and common sense seem to support one another in explaining this.

When a cable cools, the oil contracts into the spaces of high surface tension, that is, between tape surfaces if the tapes are tight, and leaves voids in the correspondingly thick helical spaces between abutting tape edges. These helical spaces are from 5 to 8 mils thick, about 1/32 in. wide, several hundred ft. long in an operating length of cable, and partially clogged with compound. A pressure of a few pounds per square inch, applied at the ends of the channels, has little or no effect, and the channels fill only by slow capillary action which is interrupted during the high-temperature periods of the heat cycle.

On the other hand, when a cable heats, the oil expands into the edge spaces and when they are filled, exerts pressure both along the helical columns of oil, and radially, the latter tending to stretch the sheath as the long helical columns of oil cannot be moved by pressure. Hence in every heat cycle oil is absorbed into the cable by capillarity during contraction and not driven out during expansion. This goes on until the space between the lead and core has grown sufficiently large to permit the compound to flow in response to the daily heat cycles. When this has occurred, the oil reservoirs will alternately fill and empty as the temperature changes.

If the paper tapes are applied so loosely that the capillarity between tapes is substantially equal to that in the edge spaces, contraction will occur more or less uniformly and the contracted compound, instead of disposing itself between tapes, will remain a continuous mass and will transmit pressure hydrostatically over a considerable distance. Hence, such a cable, when cooled, will not absorb oil from the reservoirs by capillarity as there are no long capillary filaments, the vacuum being distributed in bubbles, and when heated will merely experience a collapse of the bubble voids as the oil expands into them.

Cables made to pass such specifications as those of the Association of Edison Illuminating Companies or the National Electric Light Association, belong to the tight category. The pre-specification cables which gave such excellent service when not loaded to the point of accumulative heating, were of the loose category. The same applies to the best European cables, or many of them. For instance, one European cable which has proved its merit in high-voltage service is so loose that the oil-to-paper ratio, by weight, is 1.3 or about 50 per cent greater than a specification cable of American make. Such a cable does not absorb appreciable oil from the splice reservoirs. It responds to a certain extent to the heat cycles but the total absorption of oil over a long period is very slight.

The cable which was used by the Russian experimenters is very different from our American cable because the life of the

former is very low, thus making it easier to obtain cable rather than terminal failures. It would be interesting if the authors could tell us something about the characteristics of that cable, what the proportion was of oil to paper, and so forth. I believe the whole research in its completed form will be looked forward to with interest by all of us who are interested in this cable problem, the problem of cable pressures.

C. L. Dawes: The authors describe a method of verifying the accuracy of their bridge. They state: "After a measurement of the loss angle in the cable, a known non-inductive resistance R_0 was put in series with the latter and the loss angle was again determined."

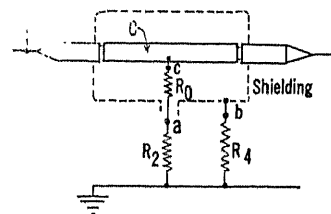


FIG. 1

The $I^2 R_0$ loss in this resistance R_0 is then calculated and compared with the increased loss as measured with their bridge. It would have been instructive if some quantitative data on these measurements had been given.

We have experimented considerably with this type of measurement and find that it must be done with considerable care. For example, in Fig. 1 herewith is shown a sample of cable with the customary shielding around the test portion of the sheath. The added series resistance R_0 is shown within the shielding. If the shielding (b) and point a are brought to the same potential by means of R_4 , as is usually done, there will be a difference of potential between points b and c equal to the voltage drop in R_0 , which may be of the order from 50 to 200 volts. This produces a considerable differential of potential between the cable sheath and its shielding. Since the capacitance between sheath and its shielding ordinarily is comparatively large, considerable error, due to shunted capacitance, may result.

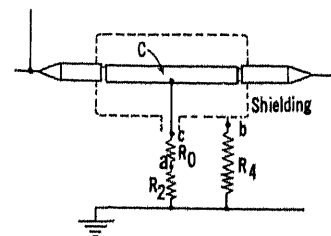


FIG. 2

This difficulty may be avoided by connecting the resistance R_0 outside the shielding, as shown in Fig. 2. R_0 must be mounted so that its capacitance to its surroundings is small. Then points c and b must be brought to equality of potential by adjusting R_4 . The sheath and its shielding, between which the capacitance is large, are now at the same potential. There is a difference of potential now between R_0 and the shielding, which will result in considerable error, unless the capacitance between R_0 and the shielding is made small. There are so many other aspects to this and related problems that I have described them in a paper, which I hope to present before the Institute in the near future.

The authors state that after the air in the cable has become ionized, the voltage in the air becomes equal to the voltage gradient of the air which is constant. That is, this voltage

gradient then becomes practically constant, independent of further increase of voltage across the cable. This statement is based on results given in a paper by P. L. Hoover and myself to which reference is made. They further state: "Hence, it follows that the loss in air at any further increase of voltage will remain constant . . ." They then derive an equation giving the variation of power factor with voltage, based on this assumption. This assumption, and hence the resulting equation, I believe, is in error. Investigations which we are now making show that after the ionization voltage is reached, the power loss becomes practically a linear function of further increase of voltage, and thus is not constant. This relationship may also be derived from curves given in Appendix IV of the paper by P. L. Hoover and myself, to which reference is made.

The authors give an explanation of the variation of life with pressure, based on the changes with pressure and voltage gradient of the losses in the air spaces, tangential components of gradient, etc. Among other reasons, they suggest that the barrier action of the insulating paper may be a function of the pressure.

For the heavy positive ions the mobility is inversely proportional to the pressure. With reduction of pressure, this tends to increase the energy of each impact. On the other hand, the voltage gradient is probably inversely proportional to the pressure, which reduces the energy of impact. Also, the number of ions available is inversely proportional to the pressure. Since the current is constant, this effect must, however, be offset either by increased ionic velocities or by a more rapid recombination which can easily occur in these restricted air spaces. Hence the net bombarding action of the positive ions probably does vary with pressure, and it is possible that its effect may be a maximum at some particular pressure, resulting in a shorter life at that pressure, as suggested in the paper.

Although some of the data and conclusions drawn by the authors are open to criticism, I feel that on the whole the paper is a contribution to our knowledge of cable phenomena, and it is particularly valuable in that it suggests a broad field for further research along these particular lines. Their attempts to reconcile power-factor variation, hours life, etc., with the behavior of ionized gas in restricted spaces is also a step in the right direction. The authors have undertaken a difficult task in making measurements of pressure, voltage, power, etc., simultaneously. The necessity of protecting the ends from flashover and yet sealing them against pressure adds to the difficulties.

W. F. Davidson: There are two points I should like to mention.

One is in connection with the arrangement of the cable for measuring power factor and dielectric loss. Referring to Fig. 4 it is noticed that the cable is suspended in the air with no apparent provision for shielding that part of the sheath which is used for the test electrode. I think that everyone who has attempted measurements of this sort will appreciate the possible considerable error here; that is, the cable will tend to pick up stray charges, and quite possibly these will be of sufficient magnitude to influence the results.

The other consideration is in connection with the method of checking the bridge and in several other cases. For some time I have been making efforts to determine the form of current wave obtained in cases where we suspect ionization to occur, as at the higher voltages considered by the authors. Our tests are not complete, but indicate that the distortion may be sufficient to introduce errors if we speak of "power factor" in the sense that implies a phase relation between simple harmonic components. The problem is even further complicated by the fact that many of the components of distortion seem to be haphazard at high frequency rather than simple overtones. Consequently, losses computed from bridge measurements are open to question, and likewise theories based on these losses.

E. H. Salter: The final test of the correctness of our theories in regard to the deleterious effect of void spaces in cable insula-

tion is the life of the cable. None of our accepted tests of cable will tell us definitely what the life—or even the probable life—will be. The test that gives us the most information on this point is the accelerated life test. While the conditions under which that test is made may have considerable effect on the results, still it gives us more reliable information as to the probable performance of cable than anything else. The authors are to be commended not only for undertaking a study of one of the most important problems confronting high-voltage cable users today, namely, what is the actual effect of internal voids, ionization, etc., on the life of cable, but also for studying the effect by means of life tests—the nearest thing to an actual service test—rather than by indirect tests based on theoretical deductions.

From the standpoint of one interested in comparative tests of cable of domestic manufacture there are several points of interest in this paper. Apparently the cable used for this investigation was of decidedly inferior quality. This conclusion is drawn from the following comparisons with normal cable of domestic manufacture:

a. The test at 60 kv. (Fig. 5) corresponds to approximately 155 volts per mil thickness of insulation (average stress gradient). At this voltage Fig. 5 shows the life to vary from 10.5 hr. with an internal pressure of 250 mm. of mercury above atmosphere to only 2 hr. with a vacuum of 300 mm. of mercury. At atmospheric pressure the life is shown as 5 hr. The average life to be expected from normal domestic cable tested at this voltage (155 volts per mil), and at pressures approximating atmospheric, is 700 hr., or about 140 times as long as shown in Fig. 5.

b. The relation between power factor and voltage is shown in Fig. 15. Here it is noted that the power-factor—voltage curve at atmospheric pressure reaches a maximum at about 37 kv., indicating that at that voltage ionization of the "void spaces" in the cable is complete. This voltage corresponds to only about 95 volts per mil of insulation (average stress gradient). In the normal domestic cable of this type ionization is not complete at voltages as high as 300 to 400 volts per mil, and in many cables has not even started at voltage gradients of the order of 95 volts per mil.

c. The cable tested was essentially high-loss cable, thus accounting for the increase in the power-factor—time curves shown in Figs. 19 and 20. Normal domestic cables of this type which have a power factor of about 0.5 per cent at 25 deg. cent. show no increase in either power factor or temperature with approaching end of life at voltages corresponding to those used in these tests.

Little mention is made of the manner of producing the pressures and vacua in the cable samples. However, what is said seems to indicate that these conditions were obtained by pumping air into, or out of, the cable. Pressure changes obtained in this manner correspond to different quantities of air in the cable, whereas in a cable in service the amount of gas present is substantially constant, pressure changes being produced by expansion and contraction of the solid and liquid components of the cable.

The fact that each pressure or vacuum in these experiments corresponds to a new and different quantity of air in the cable may affect the shape of the life *vs.* pressure curves shown in Figs. 5 to 7.

The measurement of these internal pressures and vacua requires many precautions. As indicated in Fig. 18 the correction to be applied for parasitic volumes of air in the manometer tubing, etc., may be many times the actual pressure reading. These corrections are likewise difficult to determine, especially where rubber hose, which will expand or contract with pressure changes, is used for connections. The use of a solidly connected monometer (no rubber tubing) with the lead tube filled with oil, read by bringing the mercury column always back to the same zero (no change in volume in the leads) should eliminate these corrections and their attendant errors.

The cable used in this series of tests consisted of the individual conductors of a length of three-conductor shielded-type cable. Since this is only a preliminary report, it is hoped that the findings may be augmented by similar tests on not only other types of cable, but also cable having a quality nearer that of cable now being made.

H. Connell: The company with which I am connected has been actively engaged in cable research for about a year and a half. Some of the results we have obtained, which have not as yet been published for public distribution, would lend an interpretation to the data the authors present completely different from that at which they have arrived. Therefore, while I completely disagree with their conclusions, I do not in the least mean to belittle their work.

In the first place I do not believe that the fact that they obtained like pressure readings at opposite ends of the core justifies their conclusion that that pressure represents the pressure throughout the insulation. Our experiments indicate that pressure transfer through or even along cable insulation is a slow business. Further, such pressure transfer is very markedly a function of temperature, and at temperatures less than 60 deg. cent., days and even weeks are required, at least in the case of the 3-conductor cables with which we experimented. Our pressure measurements have been made with ordinary gages oil-filled, wiped to the sheath, and with a tube extending to the center filler. In one case we had a 90-ft. length of cable arranged so that we could circulate current through it to heat it. The ends were sealed and a sylphon filled with spindle oil was connected to one of them. The sylphon was so loaded as to maintain a pressure of about 2 lb. per sq. in. On a heating cycle selected to reproduce actual service conditions we had pressures of 25, 32, and 56 lb. per sq. in. at respective distances of 21, 43, and 89 ft. from the sylphon. With decreasing current the corresponding vacua were 10, 18, and 7 in. of mercury respectively. These vacua remained sensibly unchanged for 10 hr., at which time the heating cycle was increasing the temperature again.

Our experiments on pressure transfer in a radial direction through the insulation are not as yet complete. However, preliminary results indicate that it is very slow indeed.

The terminal design used by the authors is very nice. There is every reason to believe the loss measurements indicate a value very close to the absolute value. The method of eliminating end losses is very clever.

I do not feel that the curves in which breakdown is concerned can be taken as anything more than a general trend. Breakdown in even the simplest of dielectrics is an erratic business.

The authors comment on the fact that the measured power factor in Fig. 16 lies, for high voltages, above the calculated value. This indicates to my mind that as the voltage is raised above that value giving greatest power-factor, pockets of gas which were too small to ionize at the lower voltage, ionize progressively, and thus give increased loss.

Our experiments have led us to believe that there is no reaction into which cable compounds enter, which operates to reduce their volumes materially. We further believe that there is no reaction other than oxidation in which cable compound absorbs gas during conditions similar to those under which the authors took the data for Fig. 18. We suspect that in connecting and testing their manometers they displaced sufficient compound throughout the strands of the conductor to establish a continuous air path. Upon the application of high voltage this air became ionized and activated. Under such conditions the oxygen of the air reacted chemically with the compound. The corrected vacuum curve of Fig. 18 is exactly what one might expect if such were the case. The curve has a perfectly flat top. In our explanation this is caused by all the available oxygen being used up. The pressures quoted further justify this explanation. As the curve starts from atmospheric pressure, we can find the percentage reduction in volume of any entrapped gas by dividing the maxi-

mum constant reduction by atmospheric pressure. Assuming atmospheric pressure to be 760 mm. and dividing the 156 mm. reduction by that figure, we obtain approximately 20 per cent. Ordinary air contains approximately 20 per cent oxygen.

Such oxidation is a very serious matter, as oil oxidized under such conditions is highly acidulous. We have been able to increase the acidity of a cable oil 120 per cent by exposing it for 2½ hr. to cathode rays in the presence of air. This acidity means increased dielectric loss as a certain result, and many undesirable chemical actions as probable results. The redeeming factor lies in the fact that modern U. S. cable as received from the factory contains less than 1 per cent gas by volume.

I completely disagree with the suggestions which the authors make in their fourth conclusion for curing the evils described in the first two.

In paragraph (a) they suggest the use of chemically stable compounds. Chemically stable compounds are desirable only for their ability to resist oxidation. The oil of a well built and well installed cable does not have to resist oxidation.

In paragraphs (b), (c), and (d), they suggest freely supplying air to prevent vacuum formation. Even oils of the paraffine series (the most chemically stable series) will oxidize in the presence of oxygen and a silent electric discharge. Everything known to me indicates that air must be kept out of cables, and not intentionally admitted as suggested.

In paragraph (e) they suggest that transformer oil be supplied under pressure at the joints. Sylphons filled with light oil at the joints of cable of the ordinary type will not prevent vacuum formation 20 ft. away under normal load change. They more thoroughly impregnate the immediately adjacent cable, driving the small percentage of cushioning gas normally present to the center of the length. Very high pressures and vacua result in the reimpregnated part. There may be objectionably large gas collections midway between sylphons.

E. S. Lee: When results are reported such as in this paper we are always interested in the quality of the cable insulation concerned as a basis for the applicability of the results. As Mr. Salter has shown, the samples from which these results were obtained were of what we should consider to be inferior cable.

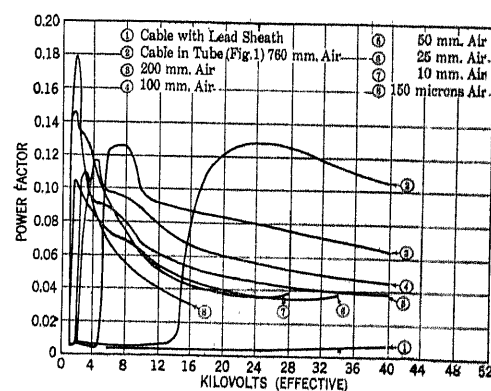


FIG. 3—VARIATION OF DIELECTRIC POWER FACTOR WITH VOLTAGE AT VALUES OF AIR PRESSURE BELOW ATMOSPHERIC

Extended application of the data reported is therefore not permitted. Since these are only preliminary results, more data will doubtless be forthcoming on samples of other quality.

The study of the internal pressure existing throughout treated-paper insulation is most important and the authors have done well to put time upon it. Figs. 3 and 4 submitted herewith show in an exaggerated way the effect upon the power factor of air pressure of different values obtained during studies of this phenomenon. The results were obtained from treated-paper insulated cable with 9/32 in. of insulation.

Curve 1 shows the power-factor variation with voltage for the normal cable with the lead sheath in place. Curve 2 shows

the result after the lead sheath was removed and a brass tube placed over the insulation with an annular air space 0.120 in. wide, making the volume of air equal to 0.68 that of the volume of the insulation. Curves 3 to 8 show the effect of reducing the air pressure. Curves 9 to 12 show the effect of increasing the air pressure. The attainment of a characteristic maximum of power factor is noted. The change in the power-factor characteristic is considerable and though exaggerated for good insulation, clearly shows the trend.

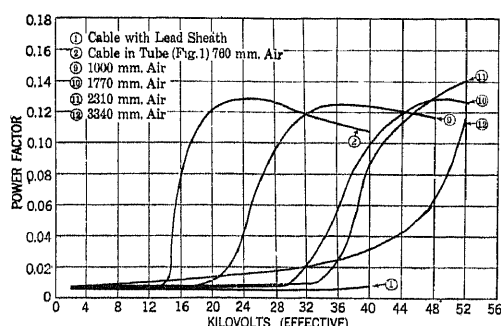


FIG. 4—VARIATION OF DIELECTRIC POWER FACTOR WITH VOLTAGE AT VALUES OF AIR PRESSURE ABOVE ATMOSPHERIC.

These power-factor characteristics correlate well with life of the insulation in that pressures of internal air below atmospheric result in shorter life while pressures above atmospheric give longer life than at atmospheric pressure.

R. J. Wiseman: I have read with great interest the paper on cables and have tried to appreciate the data presented but without success. Seeking the cause of my lack of understanding of the results, as I do not believe such results can be obtained on most American cables in view of data which have been obtained on the latter, I have made the assumption for myself that the cables on which these tests were conducted did have many vacuous spaces and, therefore, the results should be interpreted in this light. I doubt if these cables are of as good quality as can be obtained here in America. It would be of interest to us if the authors would state what the percentage saturant to paper is for these cables. If the authors found that air was being propagated along the stranded conductor, then the conductor did not have any saturant in the strands as it should have.

The paper is of value as a warning as to the conditions existing in a cable if it is not sufficiently saturated and how short the life of a cable can become under such conditions. For example, let us refer to Fig. 5. In the first place, insufficient data are given to warrant plotting such a curve. The authors could easily plot a straight line and it would be equally as accurate. However, taking the curve as drawn, the life of the cable at atmospheric pressure and a voltage of 60 kv. is only 5 hr. A good cable of this design would last about 350 hr. at this voltage, which is only three times as high as the operating voltage. We are making tests today at 3.6 times operating voltage for 24 hr. and the cable must not fail or show signs of deterioration.

We do not get a clear picture of the influence of pressure and vacuum on a cable from any of the curves dealing with the life of a cable as the life is too short even for a cable under pressure.

The curve shown in Fig. 17 cannot be taken as the true life curve of a cable if based on Fig. 5.

I cannot agree with the statement given in the third paragraph under *Losses in Cables vs. Function of the Duration of Voltage Application*, that "This shows that the chief causes of the breakdown in the cable are chemical alterations, not pyroelectric effects." If chemical changes did take place, then the oil was a most unstable one. If the failures were examined, they would probably show severe burning of the paper from ionization caused by poor saturation. In this case, breakdown was a thermal or pyroelectric effect. Breakdown, in general, is due to the ioniza-

tion of the insulation, paper and oil, which may or may not cause heat.

I suggest that the authors state in the titles to Figs. 19 and 20 that the tests were made at 60 kv.

The first three conclusions arrived at by the authors should be qualified, namely, "in poorly saturated cables." Under the fourth conclusion, I agree with "a," but "b," "c," and "d" do not sound feasible. Keep air away from a cable as far as possible. By using pressure and forcing the oil from the joint into the cable "e" really reduces the volume of the voids.

What is wanted is a cable free of all vacuous spaces; therefore, we ought to try to eliminate them. This is best accomplished by purchasing cable of high degree of saturation and then using pressure in the joints to force compound into the cable to correct for the deformations which may take place during installation. Also provide means for forcing the entrapped air out of the cable. This is done by using a higher pressure in every other joint. For example, if 10 lb. per sq. in. pressure is used in alternate joints, use 5 lb. per sq. in. pressure in the other joints. The advantage of a pressure-filled joint is obtained and at the same time the higher-pressure joints will cause the oil to move gradually along the whole cable to the lower-pressure joint and carry any air present along with it.

W. A. Del Mar: Mr. Salter gave a most interesting and admirable discussion. He started, however, with a hymn of praise of the life test which was adopted by the Russian experimenters. It is rather interesting to note that if the experimental data of the Russians are verified, it is possible to increase the life test of a cable in a way which will decrease its life in actual service. That is to say, by applying a vacuum of 5 cm. with a test voltage three times the working voltage, the life of the cable will be increased, whereas that same vacuum at working pressure would decrease the life of the cable. This suggests that there is nothing in this paper which supports the value of the life test but rather the contrary.

T. F. Peterson: (communicated after adjournment) Ordinarily I am not in sympathy with those who criticize honest attempts to get fundamental data because test conditions differ from those met in practise. In the case at hand, however, such broad conclusions and specific recommendations have been made that it may not be amiss to make certain comparisons.

The majority of the tests were made under vacua and indeed point to the superiority of one vacuum over another, (Figs. 6, 7, 8); still, conclusions concern themselves primarily with the use of internal pressure for improving cable operation. The imperviousness of impregnated paper to air passage is noted, yet no mention is made of difficulties which may be encountered in stabilizing the air pressure throughout the body of insulation for various temperatures of either the test sample or installed cable.

The seemingly peculiar "life-pressure" characteristics are due to the negatively sloping or drooping "power-factor—voltage" curve and the fact that these curves are shifted to the left as pressure is reduced. A maximum point in the "life-pressure" curve indicates that a line parallel to the Y axis of Fig. 15, through the voltage of life test, will cut negatively sloping portions of power-factor curves for pressures in the range studied. These negative slopes indicate that all air is ionized. In practise we seek to operate with no air ionized, that is, at a point on the flat part of the power-factor curve. Obviously, increasing pressure of air increases (proportionally) the voltage at which ionization (upward bend in curve) takes place. Though pressure increase is desirable it does not follow that air ducts or the like are to be recommended. Due to imperviousness of paper, temperature changes may result in undesirable pressure conditions within the body of insulation, which may exist for the long period necessary for stabilization. A perfectly filled or impregnated cable with oil ducts is far superior.

The characteristics met with in this study are due in a large measure to the negatively sloping "power-factor-voltage" curve. I take exception to the author's statement that this is due to the fact that the loss in air after ionization is constant. The gradient is constant but current through gas as well as cosine of phase angle between gradient and current varies with voltage E and so, while loss is not proportional to E^2 , it is not constant.

A complete solution follows:

Let

r_1 be radius of conductor in mils
 R be radius of inside sheath

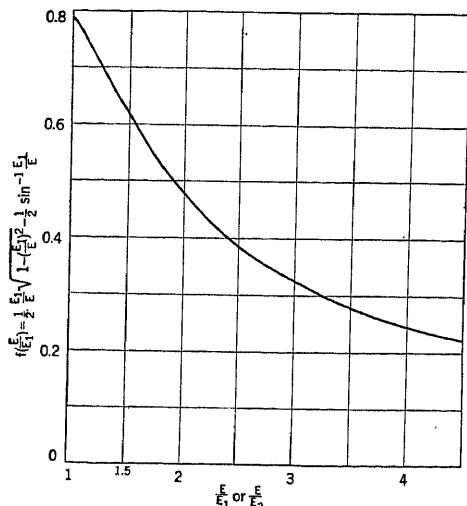


FIG. 5

n the no. of air pockets per cu. mil of insulation
 v = volume of air pocket (all assumed the same size)
 g_1 the gradient in air to break down film of thickness found

$$\frac{K_2}{K_1} = K = \text{ratio S. I. C. of paper to air} = 3.5$$

$$g_2 = \frac{g_1}{K} = \text{gradient in cable when air film breaks down}$$

i the current density through insulation

i_c the capacity current density through air film

Loss in solid insulation = $E^2 C \omega \sin \psi_2$.

Loss/unit volume of air = $g_1 i \sin \psi_1$

$$\begin{aligned} \sin \psi_1 &= \frac{\sqrt{i^2 - i_c^2}}{i} \sqrt{1 - \frac{l_c^2}{l^2}} \\ &= \sqrt{1 - \left(\frac{g_1 K_1 \omega}{g_2 K_2 \omega} \right)^2} = \sqrt{1 - \frac{g_1^2}{g_2^2 K^2}} \end{aligned}$$

$$\text{At radius } r \quad g_2 = \frac{E}{r \log \frac{R}{r_1}}$$

Loss/unit volume of ionized air

$$= g_1 i \sqrt{1 - \left(\frac{\frac{g_1}{E} K}{r \log \frac{R}{r_1}} \right)^2}$$

Total air loss =

$$\int_{r_1}^R \frac{E}{K \log \frac{R}{r_1}} v n 2 \pi r g_1 \frac{E C \omega}{2 \pi r} \sqrt{1 - \left(\frac{\frac{g_1}{E} K}{r \log \frac{R}{r_1}} \right)^2} dr \quad (1)$$

$$\text{Let } \frac{g_1 \log \frac{R}{r_1}}{K E} = c_1$$

$$\text{Total air loss} = \frac{v n g_1 E C \omega}{c_1}$$

$$\left[\frac{\pi}{4} - \frac{c_1 r_1}{2} \sqrt{1 - (c_1 r_1)^2} - \frac{1}{2} \sin^{-1} (c_1 r_1) \right] \quad (2)$$

$$c_1 r_1 = \frac{g_1 r_1}{K} \log \frac{R}{r_1} \times \frac{1}{E} = \frac{E_1}{E}$$

E_1 is voltage for breakdown of air at conductor.

$$\text{P. F.}' = \frac{\text{Loss}}{E^2 C \omega} = \frac{v n K}{\log \frac{R}{r_1}}$$

$$\left[\frac{\pi}{4} - \frac{1}{2} \frac{E_1}{E} \sqrt{1 - \left(\frac{E_1}{E} \right)^2} - \frac{1}{2} \sin^{-1} \frac{E_1}{E} \right]$$

$$f\left(\frac{E}{E_1}\right) = \frac{1}{2} \left[\frac{E_1}{E} \sqrt{1 - \left(\frac{E_1}{E} \right)^2} + \sin^{-1} \frac{E_1}{E} \right]$$

is plotted in Fig. 1. (3)

Expression (3) may be written

$$\begin{aligned} \text{P. F.} &= \frac{v n K}{\log \frac{R}{r_1}} \left[\frac{\pi}{4} - f\left(\frac{E}{E_1}\right) \right] \\ &= k_1 \left[\frac{\pi}{4} - f\left(\frac{E}{E_1}\right) \right] \quad (4) \end{aligned}$$

Expression (4) is true until all air is ionized,

$$\text{i. e., until } g_1 = \frac{E_2}{R \log \frac{R}{r_1}}$$

Upper limit in (1) should then be $r = R$

When $E > E_2$ (E_2 approx. = $\frac{R}{r_1}$)

$$\text{P. F.} = k_1 \left[f\left(\frac{E}{E_2}\right) - f\left(\frac{E}{E_1}\right) \right] \quad (5)$$

To this power factor must be added $\sin \psi_2$.

Curves from Fig. 10 of the paper by Dawes and Hoover and Fig. 16 of the present paper are replotted in Fig. 6. Knowing E , from the bend and one other point, k may be computed. The points indicated are then determined using equations (4) and (5).

$$\text{Since } k_1 = \frac{v n K}{\log \frac{R}{r_1}}$$

$$v n = K_1 \log \frac{R}{r_1} = \text{per cent air by volume}$$

= approximately 0.9 per cent for the cable

used by Dawes and considerably greater for cable used by the present authors.

The agreement of computed points and curves is close except in the case of A. This should be reduced by the per cent increase in capacity due to breakdown of air. Capacities are directly proportional to voltages across paper.

Below ionization voltage

$$E_2 (\text{across paper}) = E (1 - K n v)$$

With breakdown over insulation to distance r

$$E_2' = E - g_1 n v (r - r_1) - K n v E \frac{\log \frac{R}{r}}{\log \frac{R}{r_1}}$$

$$\frac{C}{C'} = \frac{E_2}{E_2'} = \frac{1 - K n v}{1 - \frac{g_1 n v (r - r_1)}{E} - K \frac{n v \log \frac{R}{r}}{\log \frac{R}{r_1}}}$$

Due to action of space charge, etc., the capacity changes are undoubtedly greater than this relation would indicate.

C. F. Hill: (communicated after adjournment) The results of the paper seem to point to a rather definite deterioration of paper insulation under corona in air and a decrease in life with increase in vacuum. The curve of Fig. 5 indicates a change in cable life of about five times, over the range of pressures used, but it hardly seems justifiable to assume a second peak at about 50 mm. vacuum from the data given. It may be possible to explain this general falling off in cable life with decrease in pressure as due to the increase in energy located in the ionized space and the increase averaged energy of the ions as the mean free path increases, and a minimum of this effect would be expected near the pressure for which the mean free path becomes

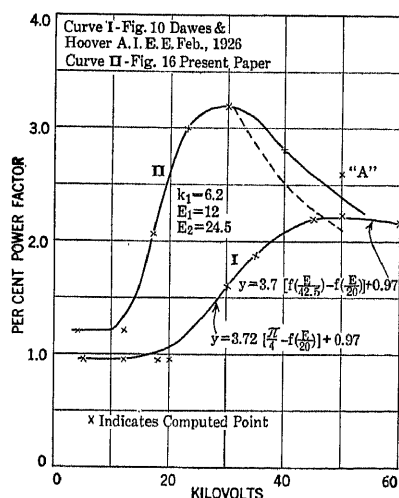


FIG. 6

equal to the spacing between layers, although the decrease in number of ions would probably raise the critical pressure somewhat. The peak values of Fig. 6 and Fig. 7 are not to be explained so easily and it is difficult to find or explain any correlation with other data of the same paper, and especially with the variation of power loss or power factor with pressure. In Fig. 18 the values for power factor remain constant even though there is considerable change in pressure.

The explanation given for the decrease in cable life with increase in vacuum is that there is a decrease in voltage drop across the air spaces with increased ionization and, of course, a corresponding increase in voltage stress on the paper. This also does not seem reasonable from the fact that the air spaces form a small part of the thickness and after the point of complete ionization the change in resistance of the air space becomes more or less negligible, so that the voltage on the paper does not change appreciably. The effect of the ionized gas in the paper seems a more logical cause for the deterioration.

The present paper coupled with that of Del Mar, read before the American Institute of Electrical Engineers in February, 1926, does, however, point out the dangers of corona in high-voltage

laminated insulation, especially where considerable stress per mil is used and where the insulation is all organic. The problem exists in all laminated insulation but low working stresses have not made it so apparent. Where mica or other insulations can be included that withstand somewhat higher temperatures, the corona does no damage, even though the corona is more or less continuously present over long periods of time. In the case of cables, it would seem that we are justified in assuming that a well impregnated cable, if it remains so, should have a rather long life. But the effects of voltage on the oil alone will collect the absorbed or residual gases into pockets and coupled with the possibilities of gases seeping in during temperature cycles, it is difficult to keep a cable free from gas pockets.

If the formation of gas pockets proves to be the cause of cable failure, a possible method of detection of the condition of a cable would be to measure the variation of watt loss with voltage applied. The loss may be expressed in terms of voltage applied as

$$\text{Loss} = K E^n$$

For good solid insulation n should remain equal to "2" over a considerable range of voltage, but if corona in gas pockets forms, n should increase above the value "2", depending on the area of the gas pockets. The possibility of getting a sensitive method for such measurements remains a matter of experimental study.

The formation of gas pockets, and these becoming ionized, also suggests an explanation of the "tree-like" paths along the plane of the paper layers in that static charges may form around or just beyond the boundary of the pocket and discharge to the ionized space. Such discharges may have enough energy under several repetitions to burn paths in the paper layer and thus start faults such as have been noted in a number of cases of cables in service.

W. N. Eddy: (communicated after adjournment) The authors find that for each life-test voltage there is a certain optimum value of the internal or void pressure, the life decreasing as the pressure increases or decreases from this value. Their results as plotted in Fig. 8 indicate that at the operating voltage (considerably lower than their test voltage), the lowest internal pressure (c) would give the longest life and the highest pressure (a) the shortest life. This is of especial interest as it is believed contrary to general experience.

In explanation of their results, they suggest that with decreasing void pressure, the dielectric loss will increase because of the decreasing ionization voltage of the voids. This will continue until all of the internal air is ionized. "With a further increase of the internal vacuum the loss will decrease, the dielectric strength of air will decrease and, therefore, the voltage drop across the air will also decrease." The last part of this explanation is not easily acceptable. It is not seen how a decrease in the dielectric strength of air can cause a decrease in the voltage across an already ionized void.

Comparison of the authors' Fig. 8 with the life-test results published in 1926 by Mr. F. M. Farmer¹ brings several pertinent indications.

1. In comparison with the variation between separate tests found by Mr. Farmer, the influence of internal pressure on the author's tests appears quite small.

2. While the slope of the authors' curves seems to increase with the internal pressure, at 200 mm. vacuum (50 cm. pressure abs.) it is the same as the average of Mr. Farmer's tests.

3. The life of the cable used by the authors is materially below what is believed to represent acceptable insulation quality.

Because of the incomplete pressure distribution throughout impregnated paper insulation if the impregnating compound is not liquid, it is suggested that each pressure given by the authors may represent that of only a small portion of the total void space in the cable. This would explain the relatively slight influence of the pressure on the life.

1. F. M. Farmer, A. I. E. E. TRANSACTIONS, 1926, Vol. XLV, *Tests of Paper Insulated Cables*.

In general, the authors' test results are of considerable interest. Because of this, it is hoped that they will continue their investigation and that tests on cable of higher insulation quality through a wider range of test voltages will be included therein.

F. M. Clark: (communicated after adjournment) This paper must be considered as a preliminary report of research investigations which have not yet been completed. Because of this, there are, no doubt, many conclusions with which one might be tempted to disagree and which probably the authors themselves may find untenable as the result of later researches. This paper, moreover, must be considered in connection with previous articles on the same subject of vacua in cables and the resulting dangers inherent with this condition.

If it does nothing more, this paper will be of value in again attracting attention to the problem of cable stability under long-time service conditions. Unfortunately it is still in some instances the practise to consider a treating compound merely as something which acts to prevent water absorption as well as to obtain the elimination of air from the dielectric. Work at Pittsfield serves to emphasize the fact that grave danger may accompany the use of a treating compound which does not possess certain specific physical and chemical characteristics. Physical characteristics in themselves appear to be of extreme importance.

The factors which influence void formation in the treated dielectric are:

1. Chemical changes in the residual gases under the influence of ionization.
2. Thermal expansion and contraction of the treating compound, and
3. Gas solubility in the treated compound.

The last of these problems has not received the attention which may be warranted by its importance. From experiments which we have carried out we have found clear evidence that the solubility of certain gases in petroleum products increases with the temperature. This may serve to explain the changes in pressure described in Fig. 18 of the paper. Presumably in cable structure we should avoid the presence of such gases. If we have present only those materials whose solubility in the treating compound decreases with increased temperature, gas areas of low pressure would be invariably absent.

The second factor involved in void formation, that is, the expansion and contraction of the compound, is a problem which appears to be difficult of solution in view of the fact that most materials available for treating purposes possess about the same thermal coefficient of expansion. However, even here I believe that considerable improvement over the present materials in common use can be made.

The problem of chemical changes in the residual gases under ionization has been described by a variety of research workers. There seems to be clear evidence that the formation of wax in cables under stress is accompanied by a gassing condition with the eventual formation of dry low-pressure gas areas.

In the conclusions drawn by the authors it is pointed out that the dangerous effect of internal vacua demands the use of chemically stable compounds. From experience in investigating this problem I should like to add that the compound should be chemically stable when no voids or gas pockets are present. To hope to obtain a compound stable to voltage in the presence of ionizing effects which accompany the application of voltage on low-pressure gas areas appears to be a hope without foundation. We have carried out a considerable number of experiments in Pittsfield and in every case we have been able to disintegrate compound-treated paper or untreated paper in the presence of air or other gases such as hydrogen. Although there are some apparent variations in the ease with which certain impregnating materials are waxed, nevertheless I believe that these variations are not important from the practical standpoint and that they

may be very largely explained by irregularities in the testing methods.

The authors have found that increased life accompanies increased pressure applied to the cable. In Pittsfield we have carried out similar experiments and have found that with untreated paper the power factor invariably increases with the gas pressure applied. We have about concluded that this increased power factor is a function of the moisture content of the gas under pressure. I wonder if the dangers from moisture contamination have been eliminated in the work described in this paper. We have also found that early failure in capacitors under voltage at high pressures has invariably been due to a change in the applied gas pressure. Any change leading to a diminished pressure will, of course, tend to remove the gas dissolved in the treating compound with the resulting formation of gas pockets. This is a factor which must be considered in work of this type and is very difficult to overcome since it is almost impossible to maintain pressures with a high degree of accuracy over long periods of time.

The authors have presented a number of interesting charts showing the relationship existing between pressure applied and resulting life and power factor. It will be of considerable importance to learn how well subsequent research work serves to check the data presented. The explanation given in the paper appeared to me, at first, to be untenable. In Fig. 18 is illustrated the change in vacuum and power factor as a result of prolonged life test. It appears to me that this increase in vacuum is what would be expected when air pockets are placed under voltage. The formation of ozone, nitrogen oxides, and the oxidation of the oil would all tend to produce such an effect. It would be interesting if the authors would carry out a similar experiment in the absence of air using hydrogen gas instead. Under such conditions it appears probable that the pressures, instead of decreasing, would increase.

The authors suggest that in general the dielectric strength of the solid insulation may depend upon the pressure of the surrounding air. This I believe is a very important suggestion which ties in very well with the research results which have been obtained in our laboratory. In fact, we have about concluded that the ordinary tests which are run on liquid and solid dielectrics are invariably a test for gas content rather than a test which involves the ultimate dielectric strength of the liquid or solid material.

The authors have found that the decrease in temperature 25 deg. cent. results in an increased internal vacuum to about 180 mm. of mercury. It appears that a number of influences must be at work to cause such a decrease in pressure. For example, I do not know the type of compound which was used in this cable but it is safe to assume that for a 25 deg. cent. change in temperature the expansion of the compound did not amount to more than 2 per cent by volume which would result in not more than 20 or 25 mm. of mercury change in pressure.

The power factor temperature curve of Fig. 19 is used as an argument in favor of the rejection of the pyroelectric theory of insulation failure. It is stated that a continual rise in temperature in the cable should result if the pyroelectric effect were of importance. I do not believe that the relation such as that shown in Fig. 19 is of considerable importance from the standpoint of the pyroelectric theory. While this theory has been, and probably still must be, modified considerably from its original form, it still appears to offer considerable promise in the explanation of those dielectric failures which are not caused by secondary effects such as chemical change in the dielectric resulting in gas formation, etc.

I want to call to the attention of the authors that the relationship between temperature and power factor is a distinct function of the experimental conditions. It is true as indicated in the paper, that the V-shape relation between power factor and temperature does exist with a minimum at about 40 deg. cent. This

appears to be irrespective of the type of impregnating materials under test. But I want to call attention especially to the fact that the minimum point in this V-shaped relation can be changed at will. In our work we have been able to shift it from 40 deg. cent. to temperatures below room temperature. We have also been practically able to eliminate the high temperature side of the V so that the power factor drops to a value which is maintained almost constant from 30 or 40 deg. cent. up to 70 or 80 deg. cent. It appears probable from our work that two different types of phenomena are brought into play when the temperature is raised on an insulation during power-factor tests. With temperatures just above room temperature the predominating factor involved has a negative temperature coefficient. With temperatures normally above 40 deg. cent. the influence involved has a positive temperature coefficient and it is this factor which is primarily concerned in normal breakdown and with which the pyroelectric theory chiefly deals.

The authors conclude, among other things, that it may be desirable to pump dry air through ducts in the core of the cable to maintain pressure higher than that of the atmosphere. This would, of course, bring about a desirable condition from the standpoint of pressure but at the same time it must be remembered that by supplying air under pressure we are increasing the amount of gas actually dissolved in the treated dielectric. Any drop in pressure, therefore, would result in the elimination of this dissolved gas and the formation of gas pockets. I firmly believe that the most dangerous single factor which could be applied to a cable under service conditions would be the pumping of air under pressure. It appears that the most likely way of maintaining high pressure inside of a treated dielectric would be the application of a hydrostatic oil head.

Alexander Smouloff: In view of the interest shown in more detailed characteristics of the cable used during the investigation, I am first giving some further information about that cable.

The ratio of compound to impregnated paper, by weight, is 45 per cent. The compound contains 50 per cent of resin and 50 per cent of naphtha-base oil having a viscosity 6 deg. Engler at a temperature 50 deg. cent. The paper used in the cable has the following characteristics:

thickness $s = 0.2$ mm.

specific density 0.7

breakdown gradient for 1 sheet 35 to 48 kv. per mm.

breakdown gradient for 2 sheets 43.2 kv. per mm.

breakdown gradient for 3 sheets 37.3 kv. per mm.

$Q = 500$ to 350 cu. cm.

$A = (0.25 \text{ to } 0.35) \times 10^{10}$

where Q is the volume of air that passed through a sample of paper having a surface $S = 10$ sq. cm. during a lapse of time $t = 60$ seconds at a pressure $h = 100$ mm. water, and A is the constant of Emanueli² from the formula $Q = \frac{I}{A \eta} \cdot \frac{S}{s} \cdot h \cdot t$.

where $\eta = 0.0001808$ is the viscosity of air.

The low quality of the cable can be chiefly explained by the unsuitable properties of the paper used and perhaps partially by an insufficient cooling of the cable before the lead sheath was put on, which certainly contributed greatly to the formation of voids or air spaces in the cable during the cooling of the sheath. Indeed another cable prepared afterwards in which another kind of paper was used, had quite different properties.

The characteristics of that paper were the following:

Thickness $s = 0.19$ mm. ($\frac{1}{3}$ of the cable's thickness)

specific density 0.72

breakdown gradient for 1 sheet 55.6 kv. per mm.

breakdown gradient for 2 sheets 52 kv. per mm.

breakdown gradient for 3 sheets 55 kv. per mm.

$Q = 20$ cm.³

$A = 6 \times 10^{10}$

Thickness $s = 0.12$ ($\frac{2}{3}$ of the cable's thickness)

specific density 0.72

breakdown gradient for 1 sheet 60.7 kv. per mm.

breakdown gradient for 2 sheets 62.5 kv. per mm.

breakdown gradient for 3 sheets 61.5 kv. per mm.

$Q = 22$ cu. cm.

$A = 8.2 \times 10^{10}$

The ratio of compound with 40 per cent resin to impregnated paper, by weight, for that cable was about 40 per cent. For the same thickness of insulation, 10 mm., the life of the cable was 50 hr. for a voltage of 100 kv. and 1 hr. for a voltage of 140 kv. The tangent of the loss angle did not change its value till the voltage of 80 kv. was reached and was always less than 0.02. Thus the properties of this cable approached the properties of cables of American make, as they were given by Mr. Salter.

Mr. Del Mar's explanation of the process of feeding cables with oil is very interesting indeed. But it is necessary to note that cables with a loose paper winding can be advantageously used only with oil feeding. I believe that normally cables must be wound as tight as possible for in that way the volume of compound is diminished, which results in the decrease of air content in the cable. The European practise is based on the belief that it is possible to manufacture cables up to the voltage of 66 kv. in such a way that the cables shall operate without oil feeding.

Mr. Del Mar explains the difference of oil and paper weights for one European cable as caused by a loose paper winding. I believe that that difference may be explained rather by the difference in the densities of the papers used in American and European practise, i. e., by a greater porosity of the paper.

In reply to Mr. Connell I must state that the propagation of pressure along the cable took place along the core and the surface of the latter. The pressures in the interior of the insulation could differ from the air pressure in the core, for, as experiment showed, the radial propagation of pressure did not take place. Oil as it is pumped in the cable passes quite freely through the core of the latter forming a jet at the opposite end of the cable. Tests were made by pumping oil into the cable out of a filter-press under a pressure up to 6 atmospheres.

Although Mr. Connell's suggestion that the formation of vacuum during the experiments could be explained by a complete using up of the available oxygen for oxidation of the compound, is supported by numerical data, nevertheless I believe that such a complete oxidation is hardly possible, inasmuch as recent researches,³ in which Mr. Connell took part, suggest that the disintegration of compounds under the influence of ionization is accompanied by liberation of hydrogen and polymerization and condensation of the particles of the compound. Even if we grant that such changes in structure of the molecules of the compound are not accompanied by change of volume of the compound, the liberated hydrogen will increase the volume of the gas although a part of the oxygen would be used up in oxidation of the compound.

By chemically stable compounds I meant such compounds as would better withstand the influence of ionization, which must depend upon the chemical structure of the compound.

In clauses *b*, *c*, and *d* of paragraph 4 of the conclusion I meant only that the cable, which was submitted to experiments, would have a longer life if the pressure of air was raised to such a value that ionization of air with all its bad consequences would not take place. However, in practise it is much better to fill a cable with oil, as suggested in clause *e* of the conclusion, for in that way the danger from ionization and oxidation is noticeably reduced. The experiment showed that by filling with oil under

3. C. F. Hirshfeld, A. A. Meyer, and L. H. Connell, "Mechanism of Cable Failure," *Electrical World*, November 12, 1927.

2. "Compte Rendu des travaux de la troisième session de la Conférence Internationale des Grands Réseaux Electriques à Haute Tension," Paris, 1925—L. Emanueli, "Une ligne expérimentale en câble fonctionnant à 130,000 volts," *T. I.*, p. 1147.

vacuum, the tested cables increased their life 7.5 times in comparison with their life without this extra oil under a vacuum of 300 mm. as such a cable could resist during 15 hr. a tension of 60 kv. when the cable was filled with oil.

In reply to Mr. Eddy's observation I would state that each experiment corresponded to a constant tension and also to a constant air pressure with a variable quantity of air in the core of the cable and around it, as the pressure was maintained constant during the whole duration of each experiment. In view of this fact, a given tension with increase of vacuum on a new cable sample made ionization take place at a lower gradient in air, which resulted in a higher tension on the solid insulation.

The volume of voids in the cable was measured directly by means of pumping oil in the cable and by means of connecting the cable under atmospheric pressure with its other end well sealed to a vessel of known volume and containing air under a known vacuum. The volume of voids measured by both methods proved to be about 30 cu. cm. per m. or 3.7 per cent of the volume of insulation. This volume corresponds to the

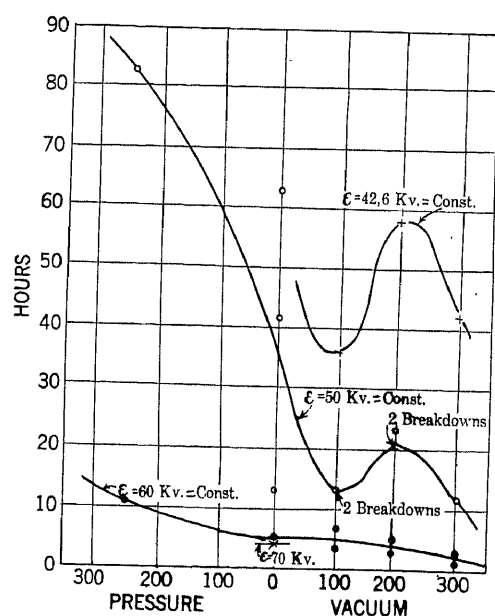


FIG. 7

space between the conductors of the core as it was checked by calculation. This shows that in the cable there was a very little quantity of compound in the core. Supplementary tests made after the paper was written show that the character of the curves in Figs. 5 to 7 holds for all pressures and voltages, as may be seen from the curves in the accompanying Fig. 7.

As regards the possibility of changes in the parasitic volumes of air in the rubber tubes to the manometer, it must be noticed that the rubber tubes were of a special rigid type with thick walls and a small diameter so that their interior volume could not appreciably change under the comparatively small pressure variations during the experiments. The connection of the manometer to the end of the cable was made by means of a rubber tube that was put on the cable insulation and on a brass cone, which allowed the use of a rubber tube of a small inner diameter. Within the cone was soldered a wire, connected to the core of the cable, from which the insulation was taken off on a length of 10 mm. The cone together with the upper electrode

was connected to the high-tension winding of the transformer. This arrangement (1) allowed an easy control of the vacuum under voltage, (2) secured the normal state of compound on the cable ends, and (3) kept away all possibility of ionization of air outside of the cable, for the brass cone acted as a screen on the wire connection to the core of the cable and on the air in the interior of the cone at the ends of the cable.

I wholly agree with Mr. Clark, that the increased solubility of gases in compounds with rising temperature is probably one of the causes of the vacua, as shown in Fig. 18.

Indirectly it could be seen from accelerated life test experiments made with cables previously heated five times during 5 min., each time with an electric current of about 800 amperes under atmospheric pressure. Between successive heatings the cables were allowed to cool during 5 min. These experiments showed a noticeable reduction of cable life. A cable submitted to such a treatment could withstand a tension of 60 kv. during 37 min. only and another a tension of 50 kv. during 42 hr., 22 min.

I am in thorough accord with Mr. Clark's statement that moisture increases the loss in paper. I have already pointed out in my paper on the "Physical Nature of Dielectric Phenomena," reported before the fourth International High-Tension Conference in Paris⁴, that moisture could act as a catalyst in the electric breakdown of an insulator, for the presence of moisture must decrease the ionization potential.

I certainly agree that it would be very interesting to make an accelerated life test with a cable filled with hydrogen to avoid the possibility of oxidation.

Mr. Clark is quite right in pointing out the danger in pumping air into a cable under pressure in cases when this pressure for some reason would be lost.

I wholly agree with Mr. Peterson that in practise cables must not be filled with air although I had in view only the results directly connected with the tested samples of cables. I cannot agree with Mr. Peterson's solution for the power factor with consideration of ionization of gas films, for this solution is not quite clear to me. I cannot see whether Mr. Peterson represents the air in a cable in the form of thin concentric air films or in the form of uniformly distributed air bubbles shunting the solid insulation. If the gradient in air to break down a film thickness found is g_1 and it is assumed that $g_2/g_1 = k = \text{constant}$, we shall always have from the formula given by Mr. Peterson $\sin \psi_1 = 0$. I believe that this power factor could be obtained in another way by assuming an in-phase ionization current in air and a leading displacement current with a conduction current in the solid insulation.

Mr. Dawes' observation of the necessity of shielding Schering's bridge and of bringing suitable points of the bridge and shielding to the same potential in order to avoid errors is quite true, but this observation holds chiefly for small capacities measured and for small loss angles, which was not the case during the experiments performed.

The assumption that the loss P_i in air remains constant after complete ionization is certainly only a first rough approximation. With an increase of current through the air under increase of voltage through the insulation there will be a variation of loss in the air. With an increase of current the voltage through the air will decrease, as always happens for ionic conduction, for instance in an electric arc, and thus the voltage through the solid insulation will increase.

4. "Compte Rendu de la Quatrième Conférence Internationale des Grands Réseaux Electriques à Haute Tension," Paris, 1927. A. Smouroff, Sur les caractères physiques des phénomènes diélectriques.

Hot Cathode Neon Arcs

BY CLIFTON G. FOUND¹

Non-member

and

J. D. FORNEY¹

Non-member

MECHANISM OF LIGHT PRODUCTION IN A GAS

THE present picture of an atom is one of a positively charged nucleus surrounded by electrons which have a definite arrangement in the normal atom. When the atomic system receives energy, it does so in a restricted manner. It cannot absorb energy continuously but only in discreet amounts which are integral multiples of a certain constant known as the quantum constant. The absorbed energy is utilized in changing the configuration of the electrons in the atom. An electron is moved farther from the nucleus to a position of higher energy content. Thus, we see that an atomic system contains a series of energy levels for the electrons. When an electron moves from an energy level, E_2 , to a lower level, E_1 , the difference is emitted in the form of monochromatic radiation, the frequency of which is determined by the relation

$$E_2 - E_1 = h \nu,$$

where ν is the frequency of radiation and h is the quantum constant. Every type of atom has a different series of energy levels, and consequently the radiation emitted by an excited atom is characteristic of that particular type of atom. Also, from the restricted nature of the energy changes, the radiation will consist of radiations of definite frequencies which will appear as a series of lines in the spectrum.

One method of transferring energy to a gas atom is by electron bombardment. An electron traveling under the influence of an electric field has an energy Ve , where V is the voltage drop through which the electron has passed, and e , the charge on the electron. If, now, the electron collides with a gas atom, part or all of the energy of the electron will be transferred to the atom, providing the restricted quantum condition is fulfilled, namely,

$$Ve \geq h \nu$$

Therefore, we may speak of energy levels in terms of voltage equivalents. For visible radiation, V has a value from 1.8 volts for the red to three volts for the violet.

A diagram for the energy levels for neon is given in Fig. 1.

It will be noted that the lowest level for neon corresponds to a voltage of 16.6 volts, which in emission is a line in the extreme ultra violet. It will be noted, also, that the level differences above this correspond to a voltage of about two volts and that the emitted radiation lies between 5800 and 7000 \AA . That is, in neon, the arrangement of the energy levels is such that practically all of the visible radiation is in the orange and red.

1. Research Lab., General Electric Co., Schenectady, N. Y.
To be presented at the Joint Meeting of the New York Sections of the A. I. E. E. and the I. E. S., May 18, 1928.

EARLY WORK ON GASEOUS DISCHARGE LIGHTS

Although the first artificial electric light was due to a gaseous discharge, we have become so accustomed to the incandescent type of lamp that we consider a gaseous discharge light as a very recent development. About 1850 Geissler first obtained light from tubes containing rarefied gases when he operated them in

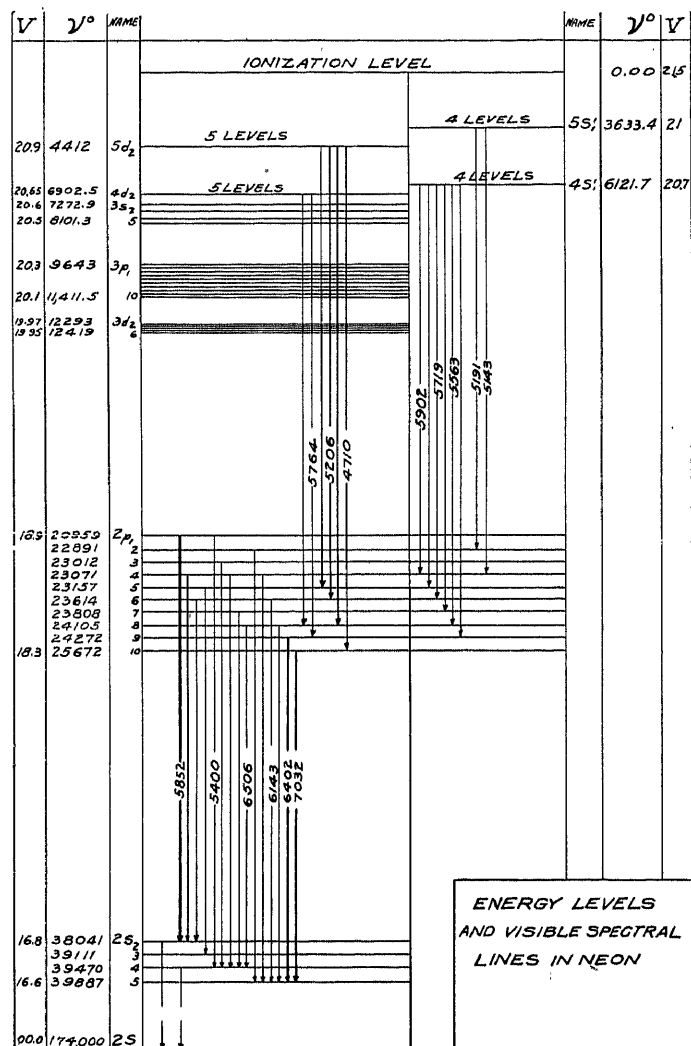


FIG. 1

connection with an induction coil. In 1893 D. McFarlane Moore started his researches on the production of light from gaseous discharges. The first commercial installation of tube lights was made in Newark in 1904 and consisted of a tube 180 ft. long operated from a high-voltage transformer. However, the commercial development of gaseous discharge lights subsided with the development of the simpler tungsten filament lamp.

CHARACTERISTICS OF A GEISSLER DISCHARGE

A consideration of the characteristics of a Geissler discharge may permit a better understanding of the difficulties encountered in the early types of tubes and of the advantages of the hot cathode. One type of Geissler discharge may take place in an elongated tube with metallic electrodes at each end. When a high voltage is applied between the plates, a discharge takes place in the tube, which has the appearance shown at the bottom of Fig. 2. This is for nitrogen at a pressure of 0.5 mm. of mercury and a current of 5 milliamperes. The tube diameter was 6 cm. Close to the cathode is a narrow, dark space, the cathode or Crook's dark space, which is followed by a luminous region a few millimeters in width, known as the cathode glow. This luminous area gradually fades into another dark region, the Faraday dark space, which extends for several centimeters. This is followed by a uniform glow or positive

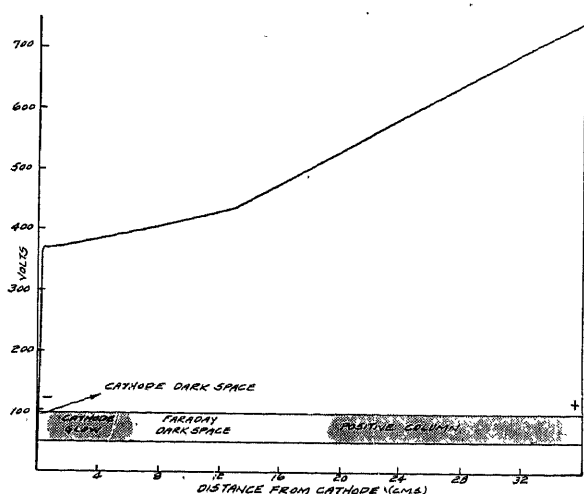


FIG. 2

column extending to the anode. The cathode end of this glow is sharply defined.

The above is the general appearance of a Geissler discharge, but the dimensions of the various regions change as the pressure of the gas and the current through the tube are altered. At low pressures the cathode dark space, cathode glow, and Faraday dark space extend a considerable distance from the cathode. As the pressure is increased, all these regions diminish in length and the major portion of the discharge is made up of luminous positive column.

Using the method of the exploring electrode as developed by Langmuir and Mott-Smith,² the first named author has measured the potential distribution in a Geissler discharge. The results for the discharge in nitrogen, mentioned above, are shown in the curve of Fig. 2. It shows the existence of a high-voltage drop at the cathode. There is also a slight gradient in

the Faraday dark space which, however, may be zero or even negative as shown by Compton, Turner, and McCurdy³ in the case of mercury. Throughout the positive column the voltage increases uniformly to the anode. The drop at the anode may be positive, zero, or negative, depending on the dimensions of the anode and the current density. However, it is always small and of the order of only a few volts. The characteristic which imposes the greatest limitations on a lamp of the Geissler discharge type is the high voltage drop at the cathode. In the above case, this is 50 per cent of the total drop in the tube and is of the order of hundreds of volts. At higher current densities the cathode drop increases and may reach over a thousand volts. On account of the important part the cathode drop plays in these discharges, we shall consider it more fully.

THEORY OF THE CATHODE DROP

As pointed out earlier in this paper, we must have electrons present in order to excite the gas atoms. Although we know very little concerning the origin of the primary electrons which cause ionization, it is generally believed that the discharge is maintained by the emission of electrons from the cathode which multiply by ionization by collisions. The exact mechanism of the process of the emission of these electrons is not known, but it doubtless is a result of bombardment of the cathode by positive ions. K. T. Compton and P. M. Morse⁴ have developed a theory of the cathode fall in a Geissler discharge which is based on this process and which fits satisfactorily the present experimental evidence and also satisfies the known empirical relations. According to this theory practically all the current at the surface of the cathode is carried by positive ions.

In a tube with cold cathode, the positive ions strike the cathode with a high velocity due to the high cathode drop, and cause a mechanical disintegration of the cathode. This cathodic sputtering causes a blackening of the tube walls. Another result of the high cathode drop is a clean-up of the gas, causing the "resistance" of the tube to increase as the tube is operated. Also, there is a large consumption of energy at the cathode which yields no light and greatly decreases the efficiency. To avoid this large energy loss and consequent heating effect, and in order to decrease the amount of sputtering, the current density at the cathode of a Geissler tube has usually been chosen at about 10 milliamperes per sq. cm.

Thus, we may summarize the effects of the high cathode drop as follows:

1. It is impossible to construct a low-voltage tube.
2. In order to have good light efficiency, it is
3. Compton, Turner, and McCurdy, *Phys. Rev.*, 24, 659, Dec. 1924.
4. K. T. Compton and P. M. Morse, *Phys. Rev.*, 30, 305, Sept. 1927.

2. Langmuir, *G. E. Review*, Nov. 1923. Langmuir and Mott-Smith, *Phys. Rev.*, 28, Oct. 1926.

necessary to make long tubes in which the ratio of cathode drop to total voltage is decreased.

3. There is a "clean-up" or disappearance of the gas. This may occur from other causes also, but is certainly increased due to the high cathode drop.

4. Blackening of the tube is caused by cathodic sputtering and in order to keep this low, there is a limit to the current density at the electrodes.

EFFECT OF USING HOT CATHODE

What is the effect of replacing the cold cathode by a heated one capable of emitting electrons in sufficient numbers to supply the current through the tube?

There is no longer any necessity for the high voltage drop at the cathode as we already have plenty of primary electrons. All that is needed is a voltage sufficient to cause ionization of the gas. This voltage is never greater than 25 volts. Thus, the substitution of a hot cathode reduces the cathode drop to a few volts and we avoid all the difficulties caused by the high cathode fall in a cold cathode discharge. In other words, the replacement of the cold electrode by a hot electron-emitting one causes the discharge to pass from a glow to an arc, as defined by K. T. Compton.⁵ His definition states: "An arc is a discharge of electricity between electrodes in a gas or vapor which has a negative or practically zero volt-ampere characteristic and a voltage drop at the cathode of the order of the minimum ionizing or minimum exciting potential of the gas or vapor." By an adjustment of the pressure, the region of cathode glow and Faraday dark space can be greatly reduced, so that the main portion of the tube is filled with the luminous positive column.

CONSTRUCTION OF HOT CATHODE ARCS

In the previous paper, Dr. Hull has described the construction of a cathode capable of supplying very large currents. This type of cathode has been used in

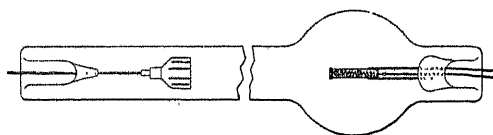


FIG. 3

the construction of the neon tubes to be described in the remainder of the paper. A further description of this cathode seems unnecessary. The radiation type of cathode has a decided advantage over a filamentary cathode in the fact that large areas can be obtained without using excessive heating currents, as in the case of heavy filaments, and also without having a large voltage drop between the terminals as in the case of a long filament. In the latter case, if the voltage across the filament is much greater than the ionization voltage of the gas used, an arc is formed across the leads and the filament is burned out.

5. K. T. Compton, A. I. E. E. TRANS., Vol. XLVI, 1927, p. 868.

The construction of a hot cathode neon tube is shown in Fig. 3. It consists of an elongated tube on one end of which is a cathode of the type mentioned, which is capable of giving an electron current of about 3.5 amperes when the heater is taking 60 watts. At the opposite end is an iron electrode which serves as anode. The pressure of neon in the tube is about 2 mm. of mercury. At this pressure practically all of the tube is filled with positive column.

ELECTRICAL CHARACTERISTICS OF DISCHARGE

Before mentioning the characteristics of the tube as a unit, we should like to discuss some characteristics of the discharge within the tube. Using the exploring electrode method, measurements of the potential distribution in a hot cathode neon tube show a cathode drop of about 25 volts followed by a uniform gradient throughout the tube. The drop at the anode varies from a few volts positive to a few volts negative, but is never very different from zero.

POTENTIAL GRADIENT AS A FUNCTION OF PRESSURE, CURRENT, AND TUBE DIAMETER

1. Pressure.

Measurements of the potential gradient as a function of the pressure show a flat minimum at from 2 to 5 mm. pressure as shown in Table I.

Pressure	Gradient
0.2 mm.	1.95 volts/cm.
0.6	1.90
1.5	1.72
2.3	1.65
3.1	1.65
4.25	1.61
4.9	1.80

2. Discharge Current.

The voltage-current relation in the main portion of the discharge is shown in Table II. The voltage gradient decreases as the current increases, giving a negative "resistance" to the discharge.

Current	Gradient
0.5 amps.	2.1 volts/cm.
1.0	2.0
2.0	1.95
3.8	1.87
6.8	1.78

3. Tube Diameter.

Table III shows the relation between tube diameter and potential gradient.

Tube diameter	1.28 cm.	1.95 cm.	2.55 cm.
Gradient	3.36 volts/cm.	2.15 volts/cm.	1.75 volts/cm.
Product	4.20	4.17	4.45

This result is in accord with the theory of Shottky⁶ who has deduced from theoretical considerations on the rates of diffusion of ions and electrons to the walls that the voltage gradient should vary inversely as the tube diameter. Results of Claude⁷ on tubes filled with neon at a pressure of 2 mm. also give results in agreement with Shottky's equation.

OPERATING CHARACTERISTICS

The over-all voltage-current relation for a tube 125 cm. long and 2.2 cm. diameter is shown in Fig. 4. On account of the negative "resistance" characteristic of the tube, the latter is inherently unstable and requires a resistance in series for stable operation. The value of this resistance must be greater than the resistance corresponding to the slope of the volt-ampere curve or the tube will not operate. It will be noted that for low currents, much greater series resistance is

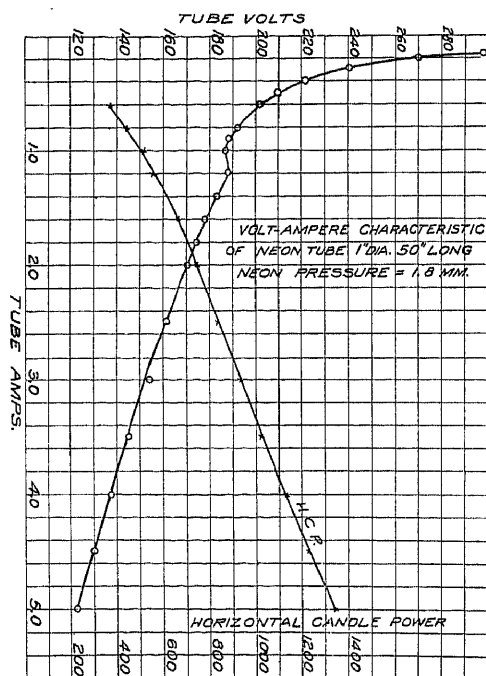


FIG. 4

required, and also the change in slope is greater at low current values. Therefore, for most stable operation, it is desirable to operate at a current where the change in slope is least, as at this point a larger proportion of the available voltage can be utilized in the tube. Also, an inductance in series with the arc eliminates transients and permits steadier operation.

STARTING OF TUBES

On a tube in which the distance from the walls to the cathode is small compared to that between electrodes, the walls of the tube become negatively charged and it is necessary to remove this charge before a discharge will pass. This is true in the present tubes and

there are three methods by which the tubes may be started.

1. A high-frequency discharge may be brought close to the tube.
2. An auxiliary anode may be placed close enough to the cathode for a discharge to take place to it. This produces ionization in the tube, which neutralizes the charge on the walls and by connecting the auxiliary and main anodes together through a suitable resistance the discharge can be transferred to the main anode.
3. By suddenly stopping the current in an inductance in series with the discharge, a high inductive kick,

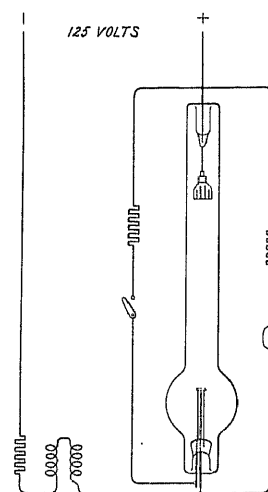


FIG. 5

which causes enough ionization in the gas to allow current to pass, is produced in the main circuit. This type of starting device is used in the Cooper-Hewitt mercury vapor lamps and is the method we have employed for the tubes we will describe below.

TYPES OF TUBES

1. *D-c. Tubes.* The circuit for a d-c. tube with stabilizing resistance and series inductance is shown in Fig. 5. In this tube the heater wire is so chosen that it requires the same current as the discharge. After the cathode is heated by means of the auxiliary circuit, the latter is opened and the discharge, which has been started by an inductive kick as described in the third method of starting, passes through the heater which now takes the place of part of the stabilizing resistance. This is a decided improvement over a Geissler discharge form of tube since the latter can be operated on a d-c. source of voltage only by using a special high voltage generator. A hot cathode tube of this type 2.2 cm. in diameter and 75 cm. long can be operated from a 125-volt d-c. line.

When both a-c. and d-c. voltages are available, the heater unit may be operated from the a-c. supply, while the arc itself may be run on direct current. The d-c. circuit for this tube, including the circuit for the method of starting by the inductive kick, is shown in

6. Shottky, *Phys. Zeit.*, XXV, 342, 635 (1924).

7. Claude, *Comptes Rendus*, p. 479, 158 (1914).

Fig. 6. When the voltage is applied the tube is shunted by a mercury switch and a resistance which limits the current in this circuit to about one ampere. As soon as this current energizes the inductance the magnetic field from the coil tips the switch, breaking the auxiliary circuit very quickly (in less than $1/5000$ of a second).

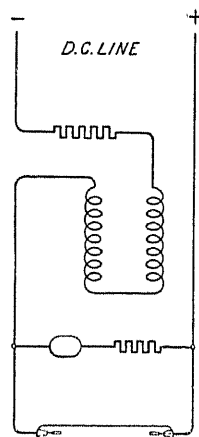


FIG. 6

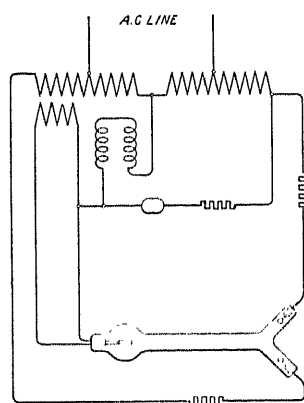


FIG. 7

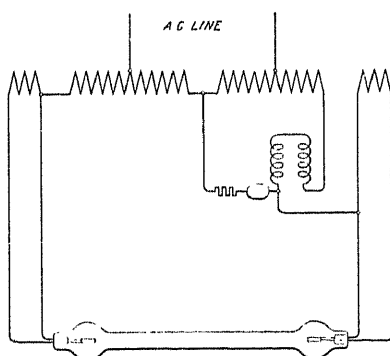


FIG. 8

This gives an inductive kick of about 2000 volts across the tubes.

2. *A-c. Tubes.* An a-c. tube is made with an anode in each of two short arms at the opposite end of the tube to the cathode. This tube, with its electrical connections, is shown in Fig. 7. The cathode is con-

nected to the midpoint of an auto-transformer through a reactance. Each terminal of the transformer is connected through a small resistance to an anode. This arrangement permits a uni-direction current to pass through the tube. The reactance causes a lag in the current so that the two half waves overlap. This reduces the current to almost a constant value and there is no visible flicker in the lamp.

Another type of a-c. tube with connections is shown in Fig. 8. A hot electrode is placed at either end of the tube and operates as cathode on one-half cycle and anode on the other. A large reactance in series with the tube is necessary to eliminate flicker.

LUMINOUS CHARACTERISTICS

Photometric measurements of a neon lamp show that as a first approximation the luminosity varies as the

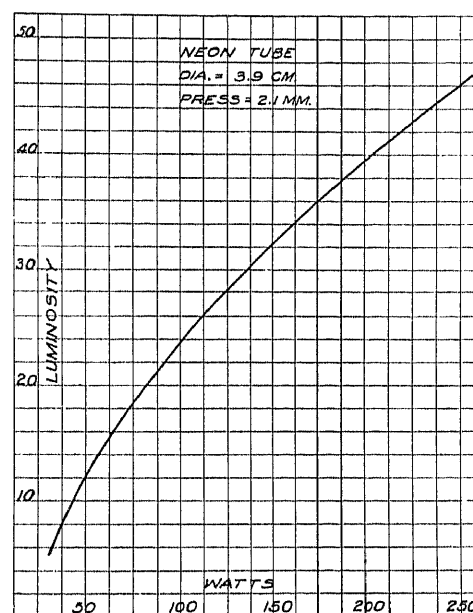


FIG. 9

$2/3$ power of the current but owing to the negative volt-ampere characteristic, the light emitted is practically proportional to the watts at higher currents, as shown in Fig. 9. These measurements apply to the positive column only. Measurements of entire tubes show an over-all efficiency of 12 to 15 lumens per watt for d-c. tubes and 10 to 12 lumens per watt for a-c., which is about the same as the 100-watt size Mazda C lamp.

A 220-volt tube, which is 2.2 cm. in diameter and 125 cm. long, operating at three amperes, has a luminous output of about 10,000 lumens.

LIFE

Tubes have been operated on life tests and many have run over 3500 hr. At the end of this period there was practically no discoloration of the walls and no measurable change in the volt-ampere characteristics of the tube. Also, from the general appearance of the

electrodes it does not appear too optimistic to predict a life of 5000 hours or more.

A feature of the tube is that its operation is independent of the surrounding temperature. Tubes have been successfully operated, without attention, exposed to all kinds of weather—rain, sleet, snow,—and at temperatures as low as -20 deg. cent.

USES OF NEON LAMPS

Display and Advertising. The color of the light emitted by neon makes it attractive for display and advertising purposes. D. McFarlane Moore did a great

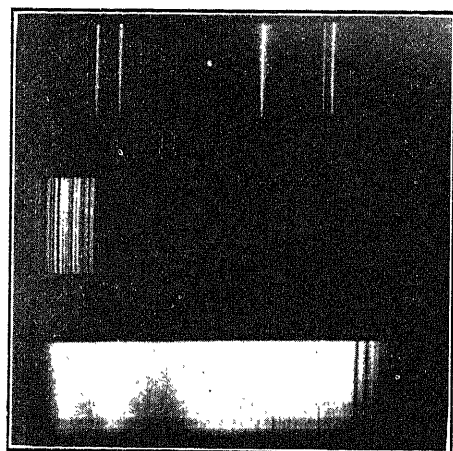


FIG. 10

deal of pioneer work in the use of gaseous discharges in nitrogen and carbon dioxide for sign work. These were of the cold cathode type. The hot cathode neon discharge is especially adaptable for display where high intrinsic brilliancy is required.

White Light and Photography. A neon lamp used in combination with a Cooper-Hewitt mercury lamp supplies the red which is missing in the latter, and by adjusting the mixture of the two, a good approximation to white light can be obtained. This can be observed in Fig. 10, which shows a spectrum of mercury at the top, neon in the middle, and one of skylight at the bottom.

The mercury-neon combination is particularly adapted to panchromatic photography. With daylight and panchromatic films, it is necessary to use an amber filter to obtain the correct reproduction as the films are more sensitive in the blue than the red. By adjusting the mixture of neon with Cooper-Hewitt mercury lights the illumination can be made to correct for the sensitivity of the film and a filter is no longer necessary.

FOG PENETRATION

In heavy or foggy weather, transportation, especially boats and aircraft, is at a great disadvantage. Measurements made by Mr. Frank Benford⁸ show that the absorption of the longer wavelengths in thick weather

is less than that of the shorter ones. Also, general experience indicates that red can be more easily discerned than other colors. This is due not only to the fact that it has less absorption but also to its contrast with surroundings. In a fog, a great deal of the shorter wavelengths are scattered, giving rise to the glare with which every motorist is familiar. Similarly when one is looking for a light, this scattered light forms a sort of illuminated blanket which diminishes the contrast between the light source and its surroundings. When a red light is used the scattered light is minimum, thus making it easier to observe the source.

Since the hot-cathode neon lamp is one of relatively high intrinsic brilliancy, it is especially adapted for this purpose as its maximum energy occurs at about 6300 \AA . We are indebted to Mr. Benford for the spectrophotometric analysis given in Fig. 11.

As a test on the advantages of the hot-cathode neon tube in weather of low visibility, a light of this type was mounted on a pier in the Hudson River. Observations from boats during a fog have shown that it was possible to pick up the red neon light before any of the other lights in the same vicinity were observed. These results indicate that this type of tube will be of great assistance as a marker for docks and ferry slips in the harbors and if placed on a ship it would also afford protection against collision with other vessels.

The same properties make it desirable in aviation. Its possible uses in this field include outlining a landing

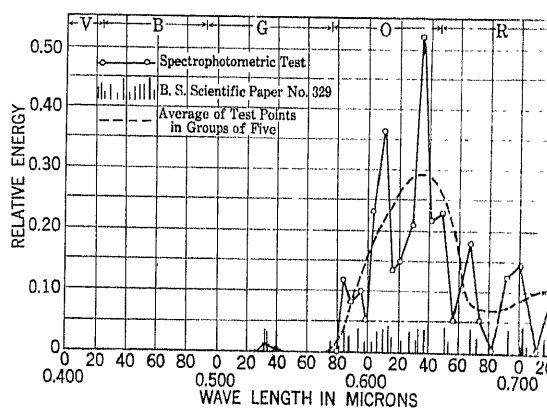


FIG. 11—SPECTROPHOTOMETRIC TEST

Neon tube No. 18,004 at 2 mm. pressure, 4.5 ampere, 121.5 volt

field, marking obstructions, and indicating a run-way. Highly concentrated tubes have been constructed for use in beacons and searchlights where a high-intensity beam is required.

In general, we believe that the hot cathode neon arc is the most efficient high-intensity source of red light we have at present.

In conclusion, the authors wish to acknowledge indebtedness to their co-workers for the great assistance which they have rendered, and especially to Dr. Saul Dushman, whose interest and suggestions have been of material help in the development of these tubes.

8. Frank Benford, *General Electric Review*, Oct. 1926.

Gas-Filled Thermionic Tubes

BY ALBERT W. HULL*

Non-member

1. INTRODUCTION AND SUMMARY

THIS paper describes a fundamental principle of thermionic gas tube operation, by which cathode disintegration may be entirely avoided. A new type of cathode is also described which requires much less heat energy than any hitherto used. With these improvements hot cathode gas tubes appear to be practical, and their fundamental characteristics as lamps, rectifiers, and "thyratrons" are briefly described.

The idea of utilizing gas in thermionic tubes is not new. It has often been proposed for lamps, rectifiers, and amplifiers. Yet up to the present time the only successful application so far as the author is aware is the "tungar" rectifier, which operates within a very restricted range of current, voltage, and gas pressure.¹ Outside of this narrow range, all attempts to use gas in thermionic tubes have resulted in unsatisfactory operation and short life. The principal symptom of failure has been disintegration of the cathode, a result so universal that it has come to be looked upon as inevitable.

The starting point of the developments described in this paper was the discovery² that disintegration is produced only by the impact of ions of more than a definite kinetic energy. The critical value lies between 20 and 25 volts for the common inert gases. Any precaution which avoids the presence of ions faster than this will prevent disintegration.

The simplest precaution is to adjust the circuit resistance so that the total "cathode drop" does not exceed this critical value, which may be called the *disintegration voltage*. Fortunately, the disintegration voltage is in all cases considerably above the ionizing potential, so that it is possible to obtain the ionization necessary for carrying large currents without exceeding the disintegration voltage. In properly constructed

tubes the necessary and sufficient condition for keeping the cathode drop within safe limits is that the cathode electron emission shall be equal to the maximum current demand.

With this precaution, the immunity to disintegration, or sputtering, is quite general. Any type of cathode can be operated without disintegration in any inert

gas, at any pressure between $\frac{1}{1000}$ mm. and 5 cm., and

with any current up to the maximum vacuum electron emission of the cathode. It is doubtful whether currents very much greater than the vacuum emission can ever be obtained without disintegration.

The *maximum current* that a tube can carry appears to be unlimited except by the size of the cathode. Cathodes have been made which furnish 1500 amperes

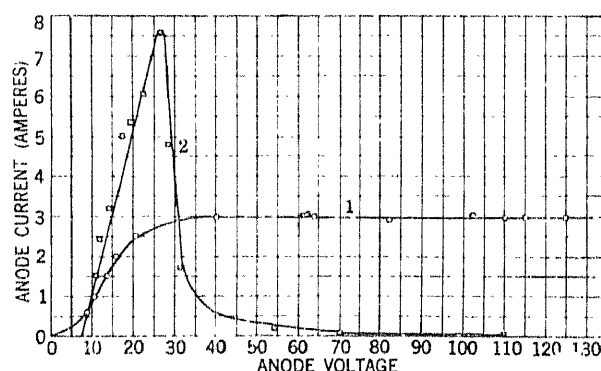


FIG. 1 VOLT-AMPERE CHARACTERISTICS OF TUNGSTEN FILAMENTS IN ARGON AT 0.030 MM. PRESSURE

Curve 1. Pure tungsten at 2450 deg. K.
Curve 2. Thoriated tungsten at 1900 deg. K.

emission under conditions which promise long life; and cathodes with a normal emission of 10,000 amperes appear quite practical.

The *maximum voltage* which can be rectified, or controlled, is limited only by the glow potential of the gas. The rectifiers and thyratrons described below operate satisfactorily at 10,000 volts, d-c., output.

Efficiency and *life* are inverse functions in high vacuum tubes. In gas tubes, however, it is possible to use heat-insulated cathodes which lose so little heat by radiation that the question of cathode efficiency can be disregarded and operating conditions adapted to long life. A total tube efficiency of 98 per cent, including both anode and cathode losses, at 500 volts operating potential, is easily attained under conditions which promise a life of many years. This efficiency is more than double that of the mercury arc rectifier and, like it, is nearly independent of load factor.

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1. During the progress of this work, Wehnelt-cathode rectifiers containing low-pressure neon have been produced in Germany, and are in use in the German post office system. They have an internal voltage drop of 17-30 volts, and are capable of rectifying 1 ampere at several thousand volts. (A. Guntherschulze, "Electric Rectifiers and Valves.") A special kind of hot cathode rectifier containing low-pressure argon was described by Germerhausen, *Helios*, Vol. 26, pp. 257-60, 1920. The Wehnelt filament was operated at very high temperature, and its loss of active material compensated continually by sublimation from a rod of alkaline earth salt. The author is not aware that these rectifiers have ever come into general use.

2. A. W. Hull and W. F. Winter, *Phys. Rev.* 21, 211, 1923. (Abstract.)

Presented at the Joint Meeting of the New York Sections of the A. I. E. E. and the I. E. S., May 18, 1928.

Hot cathode controlled rectifiers, or *thyatron*s, in which a grid is interposed between cathode and anode, have made possible the control of an output of several kilowatts by the application of one microwatt to the grid.

2. DISINTEGRATION VOLTAGE

If argon at 1/10 mm. pressure is introduced into a two-electrode tube with thorium-coated¹ cathode, one

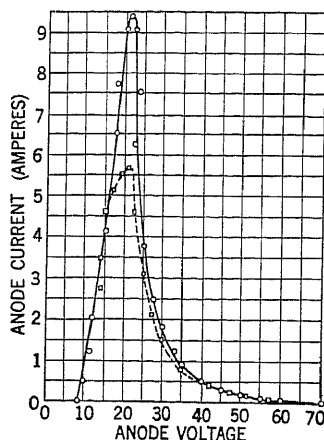


FIG. 2—CHARACTERISTIC OF THORIATED FILAMENT IN ARGON¹ AT 1900 DEG. K.

Full curve, increasing voltage; dotted curve, decreasing voltage

may obtain the volt-ampere characteristic shown in Curve 2, Fig. 1. The "pure electron" current at voltages below 15 is too small to show, being limited by space charge to a few milliamperes. At about 15 volts, ionization begins and the current rises rapidly, due to neutralization of the space charge by positive ions.³ This

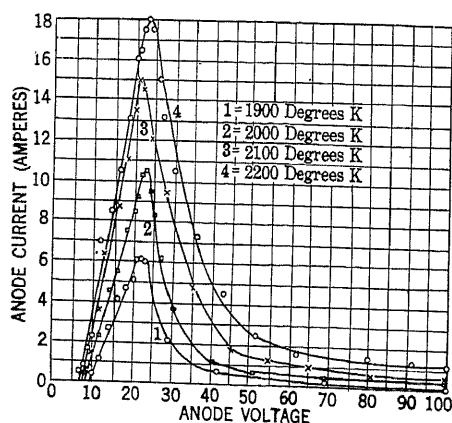


FIG. 3—CHARACTERISTICS OF THORIATED FILAMENT AT DIFFERENT TEMPERATURES, IN ARGON AT 0.030 MM.

part of the characteristic is familiar and is identical with that of a pure tungsten filament, shown in Curve 1, Fig. 1. At 25 volts, however, the current from the

3. The sharpness of the break at 15 volts is obscured by the alternating voltage drop along the filament. The abscissas are the voltage between the middle of the filament and the anode. The slow rise of current with further increase of voltage is due partly to this filament voltage drop, partly to a combination of more abundant ionization and secondary effects.

thoriated filament begins to decrease, and falls continually with increasing voltage to essentially zero at 125 volts. If the voltage is then gradually reduced, the current retraces its path as shown in Fig. 2. Fig. 3 shows a series of characteristics for the same tube at different filament temperatures, and Fig. 4 shows similar characteristics for a tube containing mercury vapor instead of argon.

The explanation of this unusual behavior of thoriated filaments is as follows:

The electron emission of the filament, as Langmuir has shown,⁴ is due almost entirely to a single layer of thorium atoms on its surface. The positive ions, whose presence is necessary to neutralize the electron space charge, can be present in the space only by virtue of the fact that they are drifting continually toward the cathode. They strike the cathode with the energy that they have acquired in the electric field, which, in this case, is essentially the full-voltage difference between cathode and anode. As long as this voltage difference is less than 25 volts, Fig. 1 shows that the ions have not

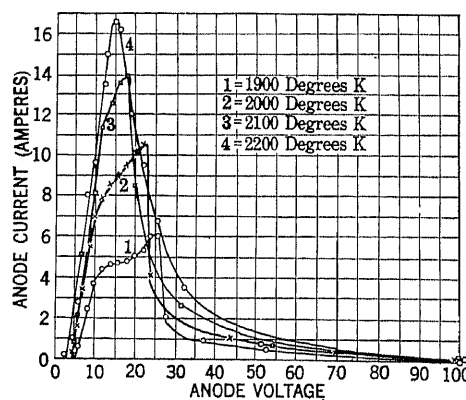


FIG. 4—CHARACTERISTICS OF THORIATED FILAMENT IN MERCURY VAPOR AT ABOUT 0.005 MM.

sufficient energy to injure the cathode. At 25 volts, an occasional ion is able to remove a thorium atom, and the probability of removal increases rapidly with increasing energy of the ions, *i. e.*, with increasing voltage. The loss of thorium is evidenced by decreased electron emission, which falls to essentially zero when half of the thorium layer has been removed.

The curves in Figs. 1 to 4 were taken with very slowly increasing or decreasing voltage, so that at each step the amount of thorium on the surface of the filament represents an equilibrium between the rate of removal by positive ions and the rate of arrival at the surface by diffusion from the interior. If the voltage is increased rapidly, all the thorium may be removed in a small fraction of a second. Fig. 5 shows the result of applying 400 volts, d-c., through a resistance of 35 ohms, and then suddenly short-circuiting the resistance. During the first part the current (Curve B) is limited by the resistance to 11 amperes, which is about half the emission of the filament, and the voltage drop between

4. I. Langmuir, *Phys. Rev.* 22, 357-398, 1923.

cathode and anode is 15 volts (Curve A, deflection downward, zero line not shown). When the resistance is short-circuited, the current first rises to the full emission value and then falls rapidly to zero, while the voltage between cathode and anode rises to the full value of 400 volts. Curve C is a 40-cycle timing wave, from which it may be seen that the time required for the current to fall to 10 per cent of its initial value is about 1/50 sec.

The current in Fig. 5 does not fall to zero, but to a small value just sufficient to remove thorium atoms as

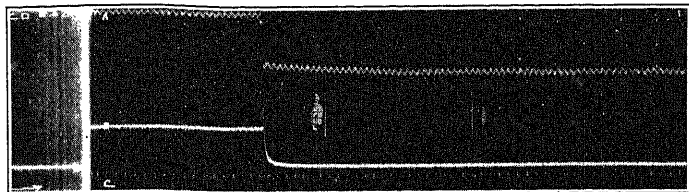


FIG. 5—OSCILLOGRAM SHOWING EFFECT OF IMPRESSING 400 VOLTS SUDDENLY UPON THE ANODE OF A TUBE WITH THORIATED FILAMENT CONTAINING ARGON AT 0.030 MM.

Curve A = voltage between cathode and anode, deflection downward.
(Zero not shown)
Curve B = current through tube
Curve C = 40-cycle timing wave

fast as they arrive at the surface from within. Removal of the voltage will allow the thorium layer to re-form, and the process may be repeated. The total amount of disintegration involved in each deactivation is essentially the single layer of thorium atoms, which is

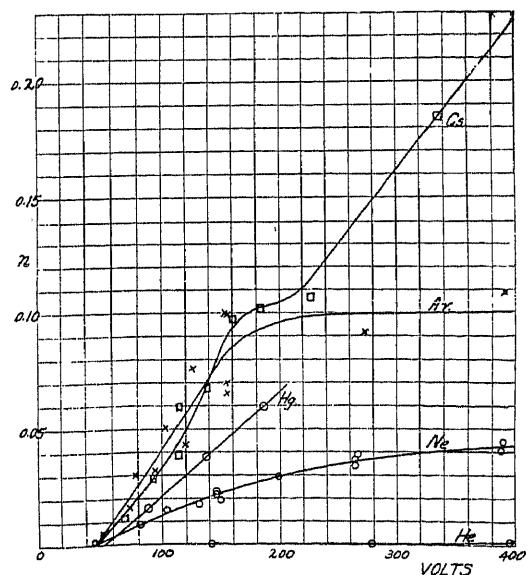


FIG. 6—NUMBER OF THORIUM ATOMS REMOVED BY AN ION AT DIFFERENT VOLTAGES (FROM PAPER OF KINGDON AND LANGMUIR.)

negligible compared with even the amount of thorium in the filament. The short-circuiting process has been repeated 1000 times in succession at 25,000 volts without any observable change in the filament.

The most significant feature of the experiments just described is not the "circuit breaking" characteristic,—

i. e., the disintegration at high voltage,—but the fact that *disintegration does not occur when the voltage is below a critical value*. This fact has been confirmed by Kingdon and Langmuir,⁵ who used cold thoriated filaments so that the number of positive ions striking the filament could be measured. In this way they obtained the number of thorium atoms removed per positive ion at different voltages (Fig. 6), and found that this number fell to zero at a definite voltage for each gas. These voltages were 45, 47, and 55 for neon, argon, and mercury respectively. Experiments similar to those illustrated in Figs. 1-4, with hot filaments and large positive ion currents, give somewhat lower values, viz., 27 volts for neon, 25 for argon, and 22 for mercury. These values are independent of temperature over the range 1900—2300 deg. K.

The rate at which thorium diffuses to the surface of a filament may be measured.⁴ This rate decreases rapidly with decreasing temperature. Since for constant electron emission the rate of gain by diffusion

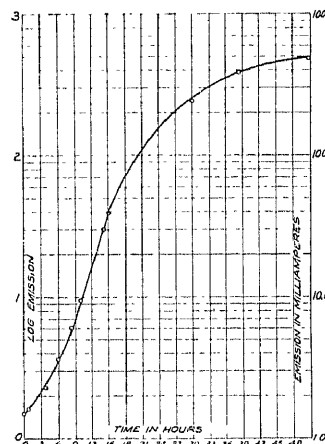


FIG. 7—RATE OF ACTIVATION OF THORIATED FILAMENT USED TO TEST DISINTEGRATION RATE, AT 1830 DEG. K.

must be equal to the rate of loss by positive ion bombardment and other causes, it is possible to obtain an estimate of the rate of disintegration by observing the lowest temperature at which the emission is constant, and measuring the rate of activation at this temperature. No attempt has been made to carry this to the limit, but a single test will give the order of magnitude. A filament which had been operating in mercury vapor at 15 volts for 3000 hr. was chosen for the test. The temperature was adjusted to 1830 deg. K., and the tube was run for several hours, with 17 volts maximum potential and 0.015 mm. pressure of mercury vapor, until it was ascertained that it was in equilibrium. The emission was constant at 0.4 ampere. The filament was now deactivated by applying 125 volts for 10 sec., then allowed to activate at the same temperature (1830 deg. K.), without anode voltage, the voltage being applied for an instant at regular intervals to observe the rate of

5. K. H. Kingdon and I. Langmuir, *Phys. Rev.* 22, 148-160, 1923.

activation. This rate is shown in Fig. 7, in which the logarithm of the emission is plotted against time. The emission of 0.4 ampere before deactivation corresponds to a surface 9/10 covered with thorium, and from the data in Fig. 7 it is found that the surface at this stage of activation is gaining in thorium atoms at the rate

$$2.6 \times 10^{13} \frac{\text{atoms}}{\text{sec.}}$$

it was losing thorium atoms during operation, and this therefore represents the rate of disintegration, assuming all the loss to be due to disintegration. At this rate, a tungsten filament 1 mm. in diameter would lose 1 per cent of its weight in 140 years.

3. HEAT INSULATED CATHODES

The efficiency of a cathode is defined as the ratio of its electron emission to the power required to maintain it at operating temperature. It is well known that the efficiency increases with temperature, while the life, which is limited by evaporation of active material, decreases. In Table I are given a few values of efficiency and life, taken from published data⁶, for common cathode materials.

In the case of high-vacuum tubes there appears to be no way of greatly increasing the efficiencies shown in Table I, except to use material of lower work function, such as caesium. No gain in efficiency can be accom-

TABLE I
EFFICIENCY AND LIFE OF COMMON CATHODES

	Temperature (Deg. Kelvin)	Efficiency amps/watt	Life (Hours)
Oxide-Coated	900	0.0086	730,000*
	950	0.015	170,000*
	1000	0.024	55,000
	1050	0.031	20,000
	1100	0.053	7,400
Thoriated Tungsten	1800	0.054*	720,000*
	1900	0.085*	94,000*
	2000	0.120*	15,100*
	2100	0.112*	2,900*
	2200	0.032*	643*
Pure Tungsten	2300	0.0008	14,900
	2400	0.0018	2,460
	2500	0.0039	450
	2600	0.008	94
	2700	0.015	23

*These values are computed and correspond to ideal conditions. They should probably be reduced by a factor of about $\frac{1}{2}$ to correspond with the other values, which are the most probable values from practical tests.

plished by changing the geometrical form, as from a wire to a ribbon, since the heat-radiating area is always the same as the electron-emitting area. Any cavity which conserves radiation, such as the inside of a closely wound helix, also conserves its electrons, *i. e.*, fails to contribute appreciably to electron emission, because the electrons are prevented by the space charge from emerging.

6. The values for oxide-coated cathodes are those furnished by the Western Electric Co. for International Critical Tables; those for thoriated tungsten are from Langmuir, *Phys. Rev.* 22, 396, 1923; for pure tungsten from W. E. Forsythe and A. G. Worthing, *Astrophysical J.*, 1925.

On the other hand, with tubes containing gas the situation is very different. Such tubes can utilize the electron emission from cavities, since the electron space charge is neutralized by positive ions. It is found that electrons freely emerge from cavities $\frac{1}{8}$ to $\frac{1}{4}$ in. wide and 4 in. deep. The maximum useful depth has not been determined. It is thus possible to employ cathodes which are heat-insulated on the outside, whose only appreciable loss of heat is that from the open end through which the electrons emerge.

The economy which can be effected by such heat-insulation of the cathode is illustrated in Figs. 8 to 11.

Fig. 8 shows an "ordinary" type of cathode, consisting of a nickel cylinder coated on the outside with barium oxide, and heated by radiation from a tungsten filament at the center. The efficiency of this cathode is in no way different from that of a filament. Its life is somewhat longer because of the absence of burn-out possibilities, especially that due to "spotting."

Fig. 9 shows an exactly similar cathode, coated on the inside instead of the outside. The electron-emitting area is the same, but only one-third as much heat energy is required to maintain it at the same temperature, hence the efficiency is three times as high. The saving is due to the reduced heat emissivity of its outside surface. Mrs. M. R. Andrews of this laboratory has measured the emissivity of nickel that has been coated with barium carbonate and heated to various temperatures. The emissivity of the coated nickel at 1000 deg. K. varies between 0.65 and 0.85, according to treatment, while that of clean nickel is less than 0.15. Taking the emissivity of the open end, which is $\frac{1}{10}$ of the total area, as 1, and that of the remaining 9/10 as 0.75 and 0.15 respectively, one obtains the ratio 3:1 for the total heat loss, in agreement with experiments. The life of the internally-coated cathode may also be expected to be longer by a factor of at least 10, since an evaporating barium atom has an average chance of less than $\frac{1}{10}$ to escape from the cylinder.

Fig. 10 shows the same cathode surrounded by two heat-reflecting nickel cylinders, which further reduce the radiation from the cylindrical surface by a factor 5.⁷ This makes the radiation from the surface, exclusive of the open end, only 3 per cent as much as from a black body or 4 per cent of that of a barium-oxide surface;

7. The author is indebted to Dr. Lewi Tonks of this laboratory for the following theorem for the heat-shielding efficiency of metallic surfaces: Assume K concentric metal surfaces all alike, of emissivity e , sufficiently close together so that the difference in radii may be neglected. The heat necessary to maintain the inner

surface at constant temperature is $\frac{eE}{2k-1-(k-1)e}$ where

E is the energy radiated by a black body of the same size and temperature. When e is small, as in the present case, this reduces

$$\text{to } \frac{eE}{2k-1}.$$

and the total loss, including the open end, $1/6$ as much as the cathode of Fig. 8. There is little to be gained by further shielding of the surface, since perfect shielding would reduce the ratio only to $1/8$. A further gain of twofold could be obtained by doubling the ratio of length to open end area, which is practical.

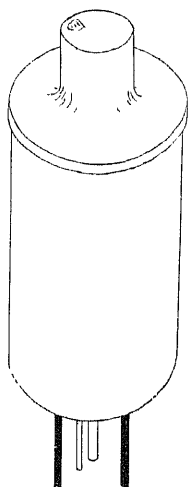


FIG. 8

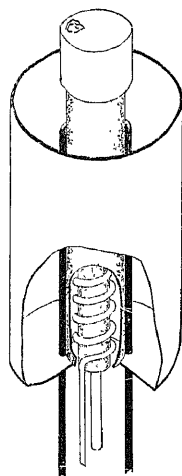


FIG. 9

FIG. 8—TYPICAL EXTERNALLY-COATED CATHODE, HEATED BY RADIATION FROM A TUNGSTEN FILAMENT AT THE CENTER

FIG. 9—INTERNALLY-COATED CATHODE OF SAME DIMENSIONS AS FIG. 8

The heat loss is only one-third as much

A greater gain is obtained, however, by the method illustrated in Fig. 11. This cathode is the same as Fig. 10 except that 16 radial vanes have been added, which are coated on both sides with active material, and form part of the electron-emitting surface. Their presence requires no additional heat, but increases the electron-emitting area fourfold. Hence the total efficiency of this cathode is 24 times that of the cathode shown in Fig. 8. It is therefore practical to operate it at a temperature of 1000 deg. K., which would give only 24 milliamperes per watt for a filament (see Table I), but for the shielded cathode gives 600 milliamperes per watt.⁸ This corresponds to a circuit loss at full load of only 1.5 volts, which is nearly negligible compared with the arc drop loss of about 10 volts. The life of this temperature would be 55,000 hr., or about 7 years for a filament, and should be greater for a cylinder, which cannot burn out and cannot easily lose its active material.

The same structure is obviously applicable to other types of cathodes, such as thorium-coated or cerium-coated tungsten or molybdenum.

Exact data are not yet available to prove that

8. This does not include the cooling effect of the electron emission which, however, appears to be very nearly compensated by the heat of condensation of positive ions and activated atoms and the radiation from the arc.

these very high values of life and efficiency are attainable. Efficiencies very close to those predicted have been obtained. For example, cathodes requiring but 200 watts give 250 amperes emission at an estimated temperature of 1100 deg. K. (cf. Figs. 20, 21). This is very close to 24 times the efficiency (53 milliamperes per watt) of a similar filament at the same temperature. It is obvious, of course, that the 200 watts merely supply the heat losses and keep the cathode at operating temperature when idle. The energy necessary to liberate the electrons, which amounts to about one watt per ampere or 250 watts total, is supplied by the kinetic energy and heat of condensation of positive ions and excited atoms and the back radiation from the arc stream. If one may speak of this energy as useful, as contrasted with the 200 watts which are wasted, the efficiency of heat utilization of these cathodes is about 55 per cent.

As regards life, the only information available is that tubes which have been operating continuously except Sundays for 6 months show no change. It is wholly probable that unexpected factors, such as chemical action, crystallization, or gradual evolution of gas, will terminate life in present tubes at times much shorter than those calculated. But it seems possible that, with development, these long life values may be realized.

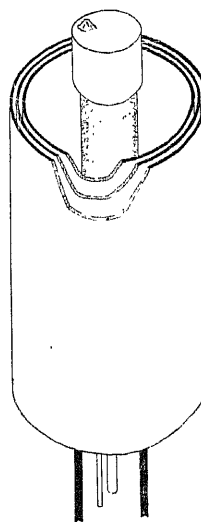


FIG. 10

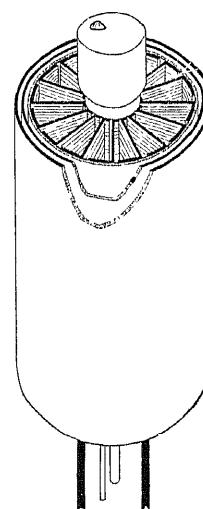


FIG. 11

FIG. 10—SAME CATHODE AS FIG. 9 PLUS HEAT SHIELDING WHICH FURTHER REDUCES THE HEAT LOSS BY A FACTOR ONE-HALF

FIG. 11—SAME AS FIG. 10 PLUS 16 ELECTRON-EMITTING VANES WHICH INCREASE THE ELECTRON EMISSION BY A FACTOR 4

The heat loss remains unchanged

4. HOT CATHODE LAMPS

The use of the hot cathode glow discharge for illumination was proposed by D. McFarlane Moore⁹ in 1905. Lederer,¹⁰ in 1914, suggested the use of a Wehnelt

9. Moore, U. S. Pat. 1010668.

10. Lederer, U. S. Pat. 1461921.

cathode in place of Moore's carbon filament for such a glow lamp, and Skaupy,¹¹ in 1915, suggested a tungsten filament.

None of these hot cathode lamps appear to have come into general use. In the case of the carbon and tungsten filaments a sufficient reason was cathode inefficiency. A 10-mil tungsten filament at 2500 deg. K. requires 236 watts of heating power per ampere electron emission. The maximum work that this electron emission can do in a 110-volt lamp is 110 watts per

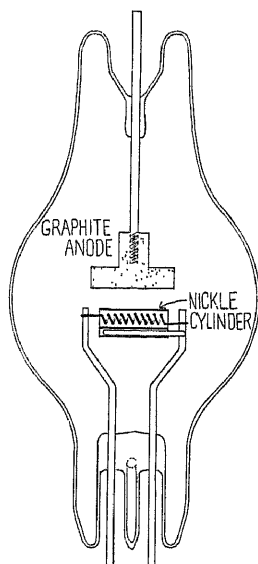


FIG. 12—TUNGAR TYPE RECTIFIER, WITH OXIDE-COATED CATHODE IN MERCURY VAPOR AT ABOUT 1 MM.

ampere, or 29 per cent of the total power supplied. The light-producing efficiency of glow discharges is not sufficiently greater than that of incandescent filaments to compensate for this waste. With Wehnelt type cathodes the waste is much less, and at moderate gas pressure it can be still further reduced by taking advantage of the "tungar effect" (cf. Section 5), so that there appears to have been no obstacle except disintegration to the use of such cathodes for lamps, at least over a certain range of gas pressure and voltage.

Both of these limitations, disintegration and inefficiency, may be removed by the measures described in Sections 2 and 3 above, and it would appear that there remains no fundamental impediment to the utilization of such hot cathode glow discharges for illumination at any pressure and in any gas that does not dissociate or attack the cathode chemically. Two subsidiary problems, disappearance of the gas and blackening of the bulb, appear to be intimately connected with cathode disintegration¹² and may be expected to disappear with it. The test data available confirm this view. Tubes containing cathodes like those shown in Fig. 9 have been operated for 2000 hr. in Hg. vapor at 0.015 mm.

with no visible blackening; and the neon lamps tested by Mr. C. G. Found show no measurable change in neon pressure after 3000 hr.

Whether or not these glow discharges will make useful lamps is quite another problem and depends on such factors as cost, luminous efficiency, color of light, convenience of operation, and degree of commercial development. Some of these factors are discussed by Mr. C. G. Found in an accompanying article. All that it is intended to point out here is that there is no fundamental obstacle in the path of such development.

5. HOT CATHODE GAS RECTIFIERS

A. Low-Voltage Tungar Type. Ordinary Wehnelt type cathodes may be operated in mercury vapor at from 1- to 3-mm. pressure for surprisingly long life at high temperature and correspondingly high efficiency. For example, a half-wave rectifier of the type shown in Fig. 12, whose cathode is a barium-coated nickel cylinder $\frac{1}{4}$ in. in diameter by $\frac{5}{8}$ in. long, requiring only 25 watts to maintain it at operating temperature, may be operated at five amperes average rectified output for 4000 hr. If operated under the same conditions in Hg. vapor at 1/100-mm. pressure, the life is less than 20 hr. The difference is due to the protective action of the gas, which tends to prevent evaporation of both barium and nickel in the same manner as in gas-filled lamps, and also appears to cause the return to the

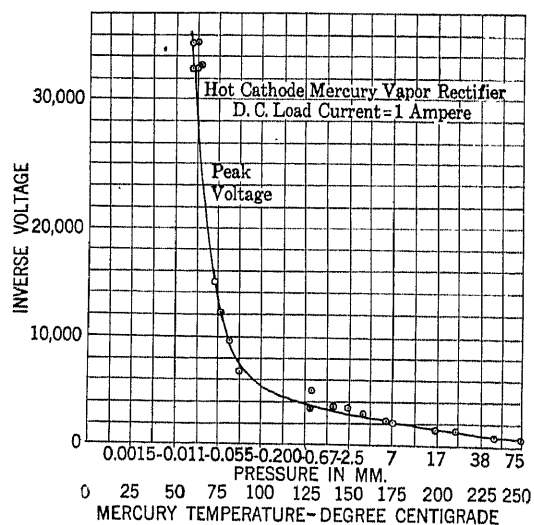


FIG. 13—VOLTAGE (PEAK VALUES) AT WHICH ARC-BACK OCCURS AT DIFFERENT PRESSURES OF MERCURY VAPOR IN THE TUBE SHOWN IN FIG. 14

cathode of nearly all evaporating barium atoms, presumably as a result of ionization by "collisions of the second kind" with excited mercury atoms. This is evidenced by the slow rate of evaporation of barium as compared with nickel. After 4000 hr. the cathode [of Fig. 12] may be reduced by evaporation to a mere lacework, yet retain its full electron-emitting activity. If operated at the same temperature in vacuum, or low-

11. Skaupy, German pat. 302806.

12. Cf. Contributions from Res. Lab. of G. E. Ltd., *Phil. Mag.* 41, 685, 1921; J. Fischer, *Fortschritte d. Chem.* 19, 1, 1927.

pressure gas, the rate of loss of barium is high compared with that of nickel, so that the electron emission is permanently lost in 20 hr.

This protective action appears to be identical with

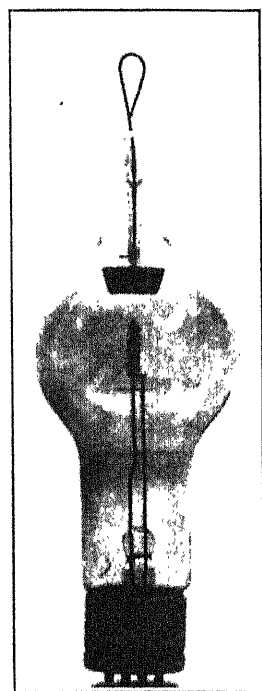


FIG. 14

FIG. 14 SMALL HIGH-VOLTAGE MERCURY VAPOR RECTIFIER, CAPABLE OF WITHSTANDING 20,000 VOLTS

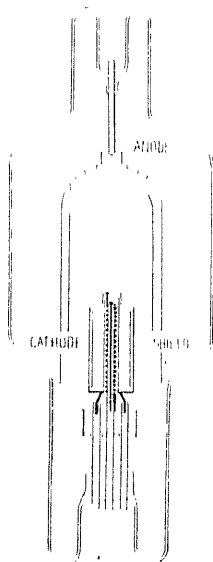


FIG. 16

FIG. 16 CROSS-SECTION SKETCH OF A 75-AMPERE GLASS RECTIFIER FOR 100-10,000 VOLTS

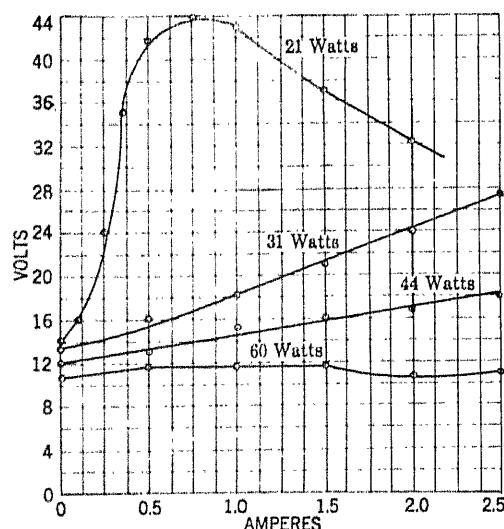


FIG. 15—ARC-DROP IN RECTIFIER OF FIG. 14, AT 0.005 MM., WITH DIFFERENT FILAMENT TEMPERATURES

The watts refer to filament heat

that which gives to the "tungar" rectifier its distinctive features, and these high mercury pressure tubes are to be classed as tungars. They are capable of rectifying

slightly higher voltages than argon-filled tungars, a rectified d-c. output of 500 volts being possible with pressures between 1 and 3 mm. (cf. Fig. 13).

B. High Voltage. For high-voltage rectification, above 1000 volts, it is necessary to use a gas pressure so low that its protective action is negligible. The maximum voltage between anode and cathode which a

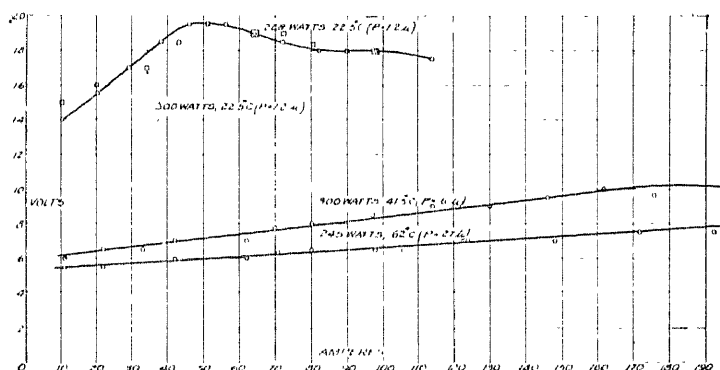


FIG. 17 —D.-C. VOLT-AMPERE CHARACTERISTICS OF FIG. 16 RECTIFIER AT DIFFERENT MERCURY PRESSURES

Watts refer to cathode heat. Note that the 228- and 300-watt curves at 22.5 deg. cent. are identical, showing that the high drop is due to low vapor pressure and not low cathode temperature

rectifier can withstand appears to be identical with the sparking potential of the gas at the existing pressure, electrode material, and effective electrode distance. The effective distance is that between the pair of points which has the lowest sparking voltage. In the case

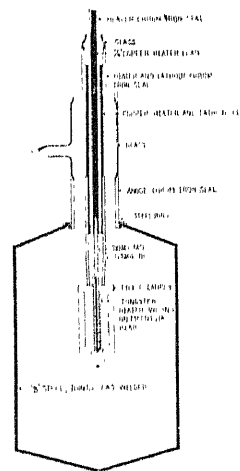


FIG. 18—CROSS-SECTION OF METAL RECTIFIER, SAME CATHODE AS FIG. 16

of rectifiers, it is not limited to actual electrode distances, since the presence of positive ions can distort the electric field so that the full voltage may exist in a thin "sheath," a small fraction of a millimeter thick, next to the cathode¹³ (the anode of the rectifier). At high gas pressures, at which the spark length corresponding to minimum sparking potential is less than

13. I. Langmuir, *Science*, 58, 290, 1923; *Jl. Franklin Inst.*, 196, 751, 1923; *G. E. Rev.* 26, 731, 1923.

the actual distance between electrodes, the space charge will automatically adjust itself to give this optimum distance. There is no lower limit to the thickness of this sheath. Hence it is easily seen that the arc-back voltage should be constant and equal to the minimum sparking potential of the gas for all gas pres-

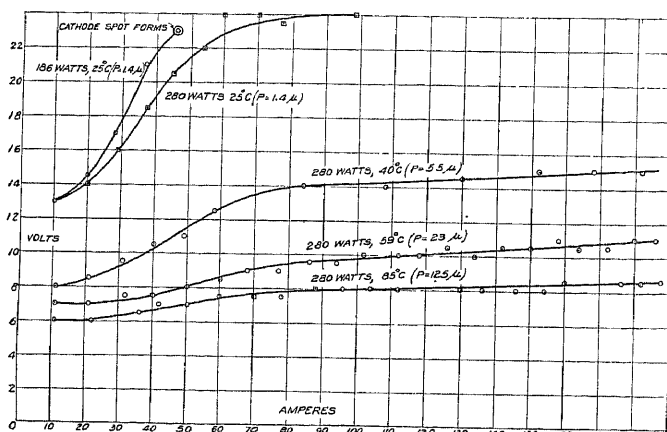


FIG. 19—D-C. CHARACTERISTICS OF METAL RECTIFIER SHOWN IN FIG. 18

The 186-watt curve shows a condition of insufficient emission, resulting in high voltage drop and cathode spot

sures higher than a certain value. This limiting value is the pressure which corresponds to the minimum sparking potential between the electrodes.

For pressures lower than this limiting value, the sparking potential is increased by shortening the distance and can be decreased only by lengthening the

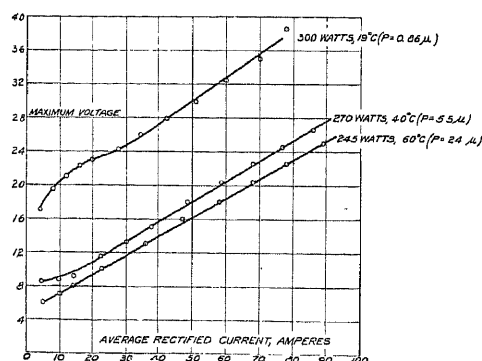


FIG. 20—MAXIMUM VOLTAGE DROP (TUBE VOLTMETER READINGS) IN GLASS TUBE WITH ALTERNATING PLATE VOLTAGE, AS FUNCTION OF AVERAGE RECTIFIED CURRENT

Note that at 19 deg. cent. the tube cannot carry more than 15 amperes without exceeding the disintegration voltage. (Tube shown in Fig. 16)

distance. But there is a definite limit to the possible length, set by the dimensions of the tube. Hence the arc-back voltage increases with decreasing pressure, and at any given pressure, is equal to the sparking potential of the gas at that pressure and at a spark length equal to the maximum possible path between electrodes. The steepness of the sparking potential-

pressure curve at low pressures is well known, and we should expect a corresponding steepness of arc-back voltage *vs.* pressure. Fig. 13 shows the results of arc-back measurements for the tube shown in Fig. 14. The abscissas are mercury vapor pressure in thousandths of a mm., the ordinates the maximum voltage which the tube could rectify without arcing back. The voltage values are maximum or peak voltages between anode and cathode, *i. e.*, the maximum reverse voltage strain which the tube can withstand. These values are quite reproducible. It will be noted that the curve is still rising rapidly at the lowest pressure used. A limiting pressure must eventually be reached where, on the one hand, there is not sufficient gas to furnish the necessary ions, and, on the other hand, the strength of the insulation and the presence of "cold cathode" electron emission set a limit to the voltage that can be used. These limits are functions of tube geometry, and cannot be stated at present.

In the current-carrying direction the potential

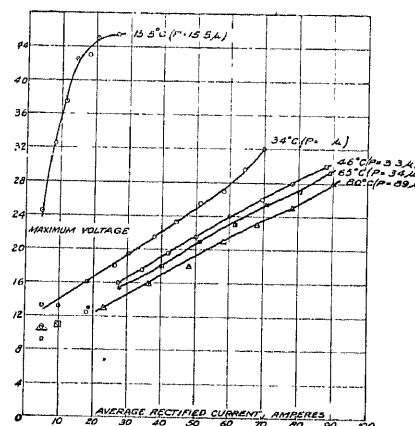


FIG. 21—SAME CHARACTERISTICS AS IN FIG. 20, FOR METAL TUBE, FIG. 18

difference between anode and cathode is and must be very low. This is the fundamental condition for cathode life, as defined in Section 2; namely, the maximum instantaneous voltage between cathode and anode in the current-carrying direction must not exceed the "disintegration voltage." Typical values of this voltage drop as a function of load current are shown in Fig. 15 for a $\frac{1}{2}$ ampere rectifier of the type of Fig. 14, and in Fig. 17 for a larger rectifier similar to Fig. 16. The values are those for steady d-c. operation, at the mercury vapor pressures indicated on the curves. The watts indicated are those required to heat the cathode. Figs. 20 and 21 give the corresponding values of maximum instantaneous voltage drop with a-c. operation, measured with a vacuum tube voltmeter. Fig. 19 shows similar characteristics for a tube of the form shown in Fig. 18, in which the iron envelope acts as anode; and Fig. 22 those of a tube similar to Fig. 16, but with a larger and better cathode, of the type shown in Fig. 11. Attention is called to the low values of heating watts shown in this figure.

It will be noted that high gas pressures favor low arc drop. This is due to the increased probability of ionization by processes other than electron impact. The total voltage between anode and cathode may fall as low as 4 volts in mercury vapor at 1 or 2 mm. On the other hand, too low a gas pressure requires that the voltage drop shall rise in order to furnish the requisite number of positive ions, and it may rise above the disintegration value. The increase is probably to be associated with anode drop rather than cathode drop. But a considerable fraction of the ions will strike the cathode with the energy of the full voltage difference, and will ruin the cathode if this voltage is above the disintegration value. The 15-deg. curve in Fig. 21 shows such a condition. Fig. 17 shows two low-pressure curves at the same pressure, but with different cathode temperatures. The curves are identical, proving that the increased voltage drop is a function of gas pressure and not electron emission. The high maximum voltages observed in the a-c. characteristics (Figs. 20 and 21) demand consideration. Examination with an oscillograph showed that they are due to sharp peaks oc-

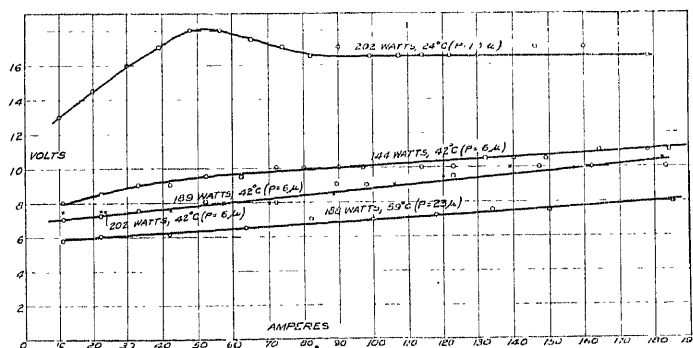


FIG. 22—D.C. CHARACTERISTICS OF TUBE SIMILAR TO FIG. 16 WITH CATHODE LIKE FIG. 11

Note that the 42 deg. curves for 189 and 202 watts are identical showing that 189 watts are sufficient for 190 amperes emission. At 144 watts the cathode temperature is too low, and the deficiency is made up by increased arc drop

curing at the beginning of each cycle. It is seen that the maximum safe rectified current at 40 deg. cent. (5.5 microns) is only 65 amperes for the glass tube and 50 for the metal tube.

The effect of low cathode temperature demands special attention. In the tests thus far described the cathode temperature has been such that the electron emission was more than sufficient for the maximum demand. If the temperature is lowered to the point where the emission is insufficient—that is, where the IR drop with maximum emission is less than the impressed voltage,—it is obvious that the voltage drop in the tube must rise. With a pure tungsten cathode, the tube continues to operate with this high-voltage drop (c.f. Curve 2, Fig. 1), with correspondingly rapid disintegration. Thorium-coated cathodes lose their thorium coating and cease to operate (see Figs. 1

to 4). The behavior of Wehnelt cathodes is a combination of these two effects, plus an increase in emission due to rise of temperature resulting from the bombardment. If the temperature of the cathode is not too high, an excess voltage will deactivate it exactly as in the case of thorium-coated cathodes, and it will remain inactive as long as the voltage is maintained, but will regain its activity if the voltage is removed for a short time. This is the best evidence available that the activity of these cathodes is due to a monatomic layer of barium atoms, presumably held by a layer of oxygen as in the case of caesium-coated filaments.¹⁴ With higher cathode temperature or high voltage, the cathode is usually heated locally by the bombardment, with rapid fluctuation of emission and dancing of a "cathode spot." An example of such a spot is seen in the upper curve in Fig. 19. On the other hand, an excess voltage drop below the critical value may cause the cathode temperature to rise uniformly until the requisite emission is obtained, and the equilibrium cathode drop is that which is just sufficient to maintain this temperature. Fig. 15 shows such a condition for a small tube, and the 144-watt curve in Fig. 22, a similar condition in the large glass tube. The agreement of the two sets of points on the lower 42-deg. curve in Fig. 22, for temperatures corresponding to 188 and 203 watts respectively, shows that the emission at 188 watts is sufficient. This is an emission of one ampere per watt supplied to the cathode. The total tube efficiency, including the arc drop of 10 volts, is 89 per cent at 100 volts for d-c. operation. For operation as a rectifier two cathodes are needed, making the total efficiency at 40 deg. cent. (5.5 microns pressure) 88 per cent at 100 volts. With the same cathode temperature and the mercury is 90 per cent at 100 volts, and 98 per cent at 500 volts.

From the test data available the operating behavior of these rectifiers appears to agree with that to be expected from the characteristics. Tubes like Fig. 14 have been operated satisfactorily for periods of 1000 hr. at 10,000 volts, d-c., output. The larger glass rectifiers, as in Fig. 16, have been tested for periods of 100 hr. at 1500 and 3000 volts, with individual outputs of 75 to 150 amperes average rectified current. It is expected that they, too, will operate satisfactorily at 10,000 volts with full output, but this has not yet been tested.

6. THYRATRONS

The name thyatron, (from the Greek *θύρα*,—a door), has been suggested for an arc whose starting can be controlled by a grid. It has been known for a long time that arcs could thus be controlled.¹⁵ They have been the subject of an exhaustive study in this laboratory, under the direction of Dr. Langmuir, for several

14. K. H. Kingdon, *Phys. Rev.*, 24, 510-22, 1924.

15. I. Langmuir, U. S. Pat. 1,289,823, Dec. 1918.

years, and the results of these investigations will soon be published by Langmuir and his associates.¹⁶ Only the specific characteristics of hot-cathode thyratrons similar to the above rectifiers, which are very simple, will be described here.

Figs. 23 and 24 show typical hot cathode thyratrons of this type. Their structure is identical with that of pliotrons except for the form of cathode and the limitations of filament voltage and grid size noted below.

Their characteristics are also the same as pliotrons *when no plate current, or very little, is flowing*. The distribution of potential in the tube is then obviously the same as in a high-vacuum tube. The amplification factor is defined, as in ordinary vacuum tubes, as the ratio of plate to grid voltage that will keep the plate current at a constant small value. This factor determines at what grid voltage the tube will "start."

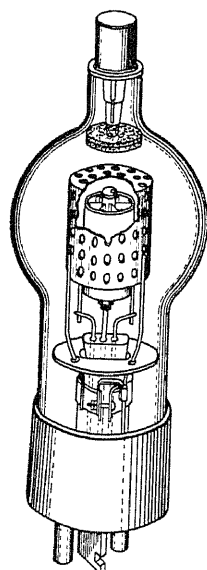


FIG. 23

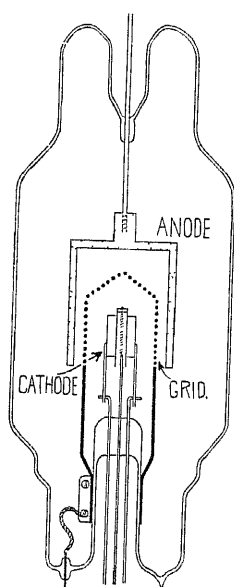


FIG. 24

FIG. 23—TYPICAL HOT CATHODE THYRATRON

The grid must not emit electrons, hence its large size

FIG. 24—COMPLETELY SHIELDED THYRATRON

This type of structure gives reproducible characteristics and favors rapid disappearance of ions

As soon as plate current begins to flow the similarity to pliotrons ends. Such factors as mutual conductance and plate resistance do not exist, for the grid is instantly surrounded by a sheath¹³ of positive ions, and has no further effect on the current.

This sheath, in general only a fraction of a millimeter thick, contains the whole voltage drop between the grid and the space surrounding it. Changing the grid voltage merely changes the thickness of the sheath, and has no effect on the potential of the rest of the space. Hence the grid is powerless to stop the plate current,

once it is started, or to influence it appreciably. It can be stopped only by removing the plate voltage.

The function of the grid is therefore obvious. It is a trigger. If it is desired to turn on a current and allow it to flow thereafter, the thyatron enables this to be done by a very small amount of power. The total energy required to turn on a kilowatt in a tube similar to Fig. 23 is less than 10^{-12} watt-seconds (1/10 microwatt acting for 10 microseconds).

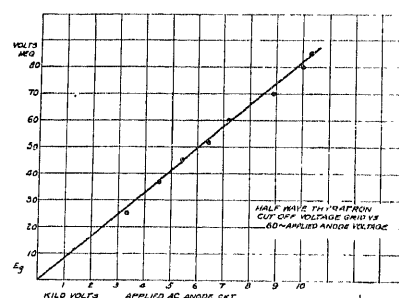


FIG. 25—CONTROL CHARACTERISTIC OF THYRATRON SHOWN IN FIG. 23

Showing grid voltage at which current starts, as a function of anode voltage

The operation of the thyatron is much more interesting, and its field of application wider, when the plate voltage is alternating. The plate current then obviously falls to zero at the end of each cycle, the ions which formed the sheaths diffuse to the walls or electrodes, and at the beginning of the next cycle the process of starting is repeated. No current will flow in this cycle if at every instant the grid voltage is more negative

than $\frac{E_p}{\mu}$ where μ is the amplification factor and E_p the instantaneous plate voltage. If at any instant the

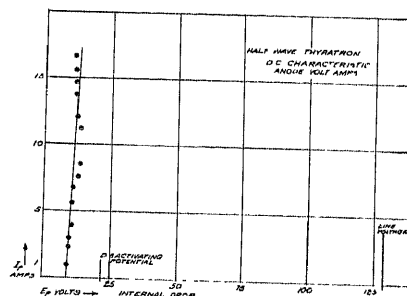


FIG. 26—VOLTAGE DROP IN THYRATRON AS FUNCTION OF CURRENT

grid voltage is less negative than this value the plate current will start and flow for the rest of the cycle. The magnitude of the plate current, once started, is limited only by plate voltage and load resistance, not by grid voltage. The *average* plate current, however, is completely determined by grid voltage, since it may allow plate current to flow during any desired number

16. See also L. Dunoyer and P. Toulon, *Comptes Rendus*, p. 179, 1924; *Jl. de Phys.*, 5, 257-68, 289-303, 1924.

of cycles in each second, or any desired fraction of each cycle. With high-frequency plate voltage the period of averaging may be very short, and if it is short compared with the period of the phenomenon to be observed an essentially continuous control is obtained. Thus audio waves of frequencies up to 5000 may be reproduced with considerable faithfulness by a thyratron with 50,000-cycle plate voltage.

These hot cathode thyratrons have the same general characteristics as the rectifiers described above, and the same requirements, especially as regards disintegration voltage. In fact, once the current is started, the grid has no more effect than a glass wall, and the behavior of these thyratrons is almost identical with that of similar tubes without grids.

In addition, the following special requirements are essential for thyratrons:

1. The maximum filament voltage must not exceed the ionization potential, unless the filament acts as a heater only and is wholly enclosed. Even then, it is hard to prevent the ions formed by this voltage from diffusing into the space around the grid, and forming a sheath which nullifies the effect of grid voltage. This requirement makes it impracticable to convert most standard plotrons into thyratrons by introducing gas, except those whose rated filament voltage is below $7\frac{1}{2}$ for mercury vapor and below 10 in case argon is used.

2. The grid must not emit electrons. For such electrons may fly freely to the anode, no matter what the grid potential, and produce ions which will sheathe the grid and make it powerless. The maximum grid emission which can be tolerated depends on the probability of ionization, and hence on voltage and geometry, but may be taken as about one milliamperere for low-voltage operation and one microampere for high voltage. The size of the grid in Figs. 23 and 24 is dictated by the requirement of grid emission. Similar tubes with smaller grids are operative when new, but become inoperative when the grid has become coated, as it usually does eventually, with active material from the cathode.

3. The grid must shield the whole cathode from the anode. In high vacuum tubes the protrusion of 5 per cent of the filament beyond the end of the grid results only in 5 per cent "zero" current, which has no effect on operation except to reduce the useful power by this amount. As a thyratron such a tube is nearly worthless. It will pass full current at all reasonable

grid voltages, since a small fraction of one per cent of the total emission is sufficient to produce ions that will sheathe the grid. The uniformity of the grid is more important than in high vacuum tubes, since the amplification factor is determined entirely by the largest hole.

This requirement of complete shielding makes even the small plotrons of most standard types unsuitable for conversion into thyratrons by introducing gas, because of the shortness of the grids.

4. The gas pressure must not be so high that the positive ions persist for a half cycle. This is a question of diffusion. The time required for the ions to diffuse to the electrodes and walls depends on the geometry of the electrodes, as well as on the gas pressure. In the tube shown in Fig. 23 the maximum pressure of mercury vapor for 60-cycle operation is 0.040 mm., while a tube similar to Fig. 24 is operable under the same conditions with 1 mm. pressure of mercury.

5. A full-wave hot cathode thyratron with two anodes in the same bulb will obviously give large positive ion currents to the grids, unless sufficient shielding is provided. Rectifiers of the same type have inherent anode sputtering, but are operable under conditions which would make thyratrons inoperable.

6. Tubes containing vapors which are ionized by contact with the cathode, like *Cs*, *Rb*, and *K*, give positive ion sheaths around the grid when the grid is negative, making operation as thyratrons difficult or impossible.

These limitations do not apply to tubes whose grid mesh is so fine that the positive ion sheaths overlap under operating conditions. These tubes can be operated in the presence of positive ions, but their characteristics are quite different from those under discussion, and they will not be considered here. The most significant operating characteristics of these thyratrons are amplification factor and voltage drop. Fig. 25 shows the amplification factor curve of a thyratron similar to Fig. 23. The values of grid voltage plotted are the "starting" voltages, *i. e.*, the values that mark the line between no current and full current. Fig. 26 shows the voltage drop as a function of load. It does not differ appreciably from that of rectifiers.

In obtaining the data presented in this paper I have had the assistance of the whole research staff, but especially of Messrs. W. F. Winter, E. P. Lawsing, H. C. Steiner, and W. A. Ruggles, whose able cooperation I gratefully acknowledge.

The Drive of Tandem Rolling Mills

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Synopsis.—The paper briefly discusses the development of the tandem type of rolling mill and the requirements of electrical drives

for such mills, and presents methods of calculation of power requirements.

CHANGING conditions in the steel rolling mills of this country have caused the development and widespread application of what are quite commonly termed "tandem" rolling mills. The tandem type of mill has the advantages of great flexibility, high tonnage output, low labor costs, compactness of layout, and uniform quality of product. This type has been applied successfully to the production of thin flat stock up to 50 in. wide, rod, bar, merchant, and structural shapes. In this type of mill, the several finishing

d-c. adjustable speed motors for the individual drive of each of the three tandem finishing stands. The arrangement of the stands is shown by Fig. 1. The distance from stand 14 to 15 was 12 ft. and from stand 15 to 16 was 15 ft. The three finishing stands were driven by direct-coupled 575-volt d-c. motors of 600 hp., 150/250 rev. per min.; 800 hp., 210/315 rev. per min.; and 800 hp., 260/390 rev. per min., capacity respectively. At the top speed of 390 rev. per min. on stand 16 motor, the delivery speed was approximately 1325 ft. per min. The mill has a range of capacity from 18 gage strip up to about 4 in. wide to 14 gage material up to about 10 in. wide. In its arrangement of the finishing stands the mill varies but little from more recent designs.

With the more recent installations the trend has been toward the elimination of stands in train, with final development of the present mills in which the

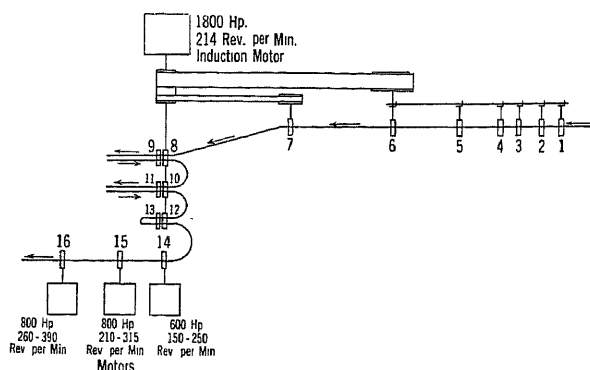


FIG. 1—14-IN. STRIP MILL AT CUYAHOGA WORKS OF AMERICAN STEEL AND WIRE COMPANY

Illustrating first application of d-c. adjustable-speed motors to tandem finishing stands Installed 1908-9

stands, and in some recent installations the roughing stands also, are closely spaced in a continuous line and are individually driven by separate motors. The length of the billets and the spacing between stands are such that a single piece of steel may be in several stands at one time, and for periods of several seconds. It is therefore essential to the successful operation of such a tandem mill that the speeds of the several driving motors be susceptible of easy and accurate adjustment, in order that stretching or looping of the steel between stands may be kept within limits.

DEVELOPMENT OF TANDEM OPERATION

During 1908-9, the American Steel and Wire Company installed at its Cuyahoga Works a 14-in. mill which is of considerable interest in that it was the first electrically driven mill for the rolling of wide strip material, and that it was the first application of separate

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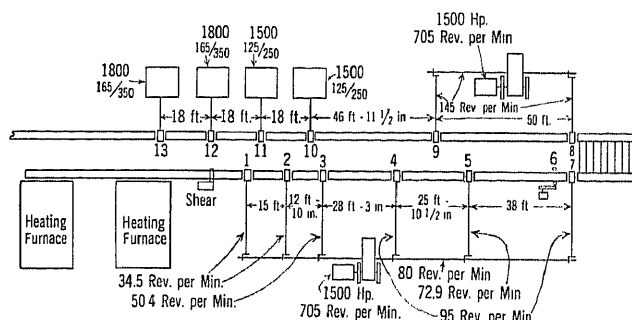


FIG. 2—20-IN.—16-IN. SEMI-CONTINUOUS STRIP MILL AT WEST LEECHBURG STEEL COMPANY

The four finishing stands are individually driven by two 1500-hp. and two 1800-hp. d-c. motors

stands are arranged in one continuous line. As an intermediate step in the development, Fig. 2 is included to show the layout of the semi-continuous mill of the West Leechburg Steel Company. The equipment and operation of this mill were described in a paper read before the April 1924 Convention at Birmingham by Jones and Wilson.

The Acme Steel Company has a mill very similar in equipment to the West Leechburg mill, but in which the stands are arranged in a single line, eliminating the broadside transfer. Also the two intermediate stands are much closer together and are driven by adjustable-speed direct-current motors. This arrangement permits of additional flexibility and permits the rolling

of finished strips up to 600 ft. or longer. Fig. 3 shows the arrangement of the mill and driving motors.

Latest designs show a tendency to apply individual motor drives to the roughing as well as the intermediate and finishing stands. A mill for the production of strip up to 50 in. wide, construction of which will soon be completed, consists of eleven roll stands, the first four driven by wound-rotor induction motors, and the last seven driven by d-c. motors. The total capacity of the eleven motors is 21,800 hp. A similar eleven stand mill will be driven by one constant-speed motor and nine adjustable-speed d-c. motors.

On the tandem stands of the mills so far discussed in this paper, d-c. adjustable-speed motors have been applied. The question may logically be asked: Why not use some type of alternating-current adjustable-speed drives? To answer this question we should consider first the suitability of such machines for tandem mill operation, and second the relative cost as compared to other drives.

It is a requirement of any continuous mill, in which steel is in two or more stands simultaneously, that the

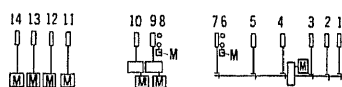


FIG. 3—20 IN.-16 IN. STRIP MILL AT ACME STEEL COMPANY

The vertical edgers and the intermediate and finishing stands are driven by d-c. motors

Pass	Diam.	Rev. Per. Min	D. to next pass	Motor hp.
1	20"	35	15'-6"	1500
2	20"	35	16'-7"	
3	20"	50	33'-0"	
4	20"	95	30'-0"	
5	20"	79	38'-7"	
6	8'-0"	100
7	20"	95	66'-0"	
8	8'-0"	100
9	16"	76-152	18'-0"	
10	16"	100-200	77'-0"	1800
11	16"	125-250	18'-0"	
12	16"	125-250	18'-0"	1800
13	16"	185-370	18'-0"	
14	16"	185-370		1800

product of delivery speed and cross sectional area of steel after the pass must be the same for each pass of the mill, else the steel will be stretched or a loop formed between stands. Speed adjustments must therefore accompany any changes in the drafts made in the various passes. Mill operators, in purchasing tandem mill drive equipment, have commonly specified that the motors should have a speed regulation of not more than 2 per cent. Analysis shows, however, that the actual speeds while steel is in the mill, rather than the difference between the friction and rolling load speeds, determine the amount of looping or stretching which will take place. Regardless of the friction-load speeds, each motor will quickly assume its loaded speed as soon

as the steel enters the rolls, and if the loaded speeds of each of the several stands are in the correct relation for the reductions being made, there will be no stretching or looping. From this standpoint successful operation can and is being obtained with motors having as much as 8-10 per cent speed regulation on the finishing stands. However, with motors of flatter speed characteristics, the speeds of the several motors may be more accurately set at no-load, and speed changes due to load variations caused by changes

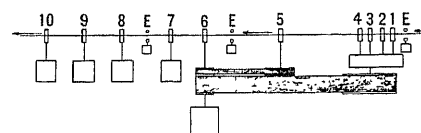


FIG. 4—10-IN. STRIP MILL OF LACLEDE STEEL COMPANY ILLUSTRATING THE USE OF A MULTI-STAND ROUGHING MILL IN TANDEM WITH INDIVIDUAL MOTOR DRIVEN FINISHING STANDS

Pass	Diam.	Rev. per min.	Motor hp.
Edger	..	275/825	100
1	12	31/63	..
2	12	45/90	..
3	12	61/122	..
4	12	90/181	..
5	11	123/249	..
Edger	..	400/1600	35
6	10	198/400	1500
7	10	185/470	600
Edger	..	400/1600	35
8	10	270/635	600
9	10	395/825	720
10	10	480/1000	720

in draft, temperature of steel, etc., are kept at a minimum. This makes a comparatively flat speed characteristic in the motors very desirable. Most operators therefore insist on motors of flat speed characteristics.

There is a type of mill, such as the 10-in. strip mill of the Laclede Steel Company, Alton, Illinois, Figs. 4 and 5, where motors of good speed regulation are quite necessary. In this mill, the six roughing stands are driven by a 1500-hp. 198/400-rev. per min. motor, and the four finishing stands are driven by individual motors of 600 hp. and 720 hp. capacity. The billets are of such length that one piece may be in all stands of the mill simultaneously.

For illustration, assume that the speed regulation of the 1500-hp. motor is 5 per cent and that the speed-load curve is a straight line. Further assume that the friction load is 100 hp. and that the rolling load of each stand is 300 hp. making a total load of 1900 hp. when metal is in all stands. In order to avoid stretching of the steel between stands 6 and 7, it is necessary to have the delivery speed of stand 6 equal to or greater than the take-up speed of stand 7. That is, the speed of the 1500-hp. motor when carrying 1900 hp. load must give a delivery speed to stand 6 at least equal to the take-up speed of stand 7. But, as the end of the strip leaves stands 1, 2, 3, 4, and 5, in succession the load on the 1500 hp.-motor is reduced, the speed increases,

and a loop is formed. Table I shows the data for a particular rolling schedule, and indicates that nearly five ft. more material will be delivered from stand 6 than is taken up by stand 7, during the interval between the time when the tail end of a piece leaves stand 1

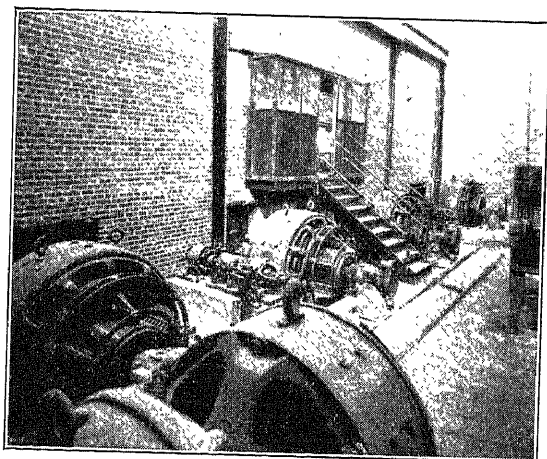


FIG. 5—TWO 720-HP., AND TWO 600-HP. D-C. MOTORS DRIVING THE FINISHING STANDS OF A 10-IN. TANDEM HOT STRIP MILL AT LACLEDE STEEL COMPANY

The series exciter set for indirect compounding of the two 720-hp. motors is shown between these motors

and the time it leaves stand 6. Remember, too, that this is on the basis that the delivery speed of stand 6, when steel is in all the roughing stands, is exactly equal to the take-up speed of stand 7, and that there is no loop formed until the tail end of the piece leaves stand 1. If, as is quite often the case, in order to avoid all possibility of stretching the normal delivery speed of stand 6 with the roughing mill full is slightly in excess of the take-up speed of stand 7, there will be an initial loop between stands 6 and 7 before the steel leaves stand 1. Then by the time the steel leaves stand 6, the loop may have become so large as to be unmanageable. When this motor was first installed, the speed regulation was of the order of 7-8 per cent, due to a misadjustment. Considerable trouble was experienced due to the exces-

sive looping of steel, until adjustments were made to reduce the speed regulation to below 2 per cent. Quite satisfactory operation is now obtained under this latter condition.

If we analyze the case of a mill consisting of two or more multi-stand sections each driven by a motor of poor speed regulation, the loop formed between sections may be much longer than in the case just considered. Referring to Fig. 6, stands 1, 2, 3, and 4 are driven by one motor while stands 5, 6, 7, and 8 are driven by a second motor. Assume again that billets are of such length that one piece may be in all stands simultaneously. Now in order to avoid stretching of the steel, it is necessary that the delivery speed of stand 4, with steel in stands 1, 2, 3, and 4, be equal to or greater than the take-up speed of stand 5, when steel is in only stand 5 of the second section. But, as the steel enters stands 6, 7, and 8, the speed of the second motor is reduced, and the take-up speed of stand 5 is lower than

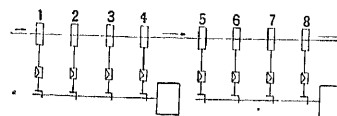


FIG. 6—EXAMPLE OF MILL CONSISTING OF TWO MULTI-STAND SECTIONS IN TANDEM, TO ILLUSTRATE LOOPING OF STEEL BETWEEN SECTIONS CAUSED BY SPEED REGULATION OF DRIVING MOTORS

the delivery speed of the preceding stand. A loop is thus formed. Also as the tail end of the piece leaves stands 1, 2, and 3, the speed of the first motor increases, and the delivery speed of stand 4 exceeds the take-up speed of stand 5 by a still greater amount, so that the rate of loop growth is accelerated.

It is to be noted that in the case of the mill shown by Fig. 4, the total length of excess material caused by the increased speed of the roughing mill due to decreased load as the steel leaves the early passes, is independent of the length of billets being rolled, and depends only on the speed regulation of the motor and on the layout

TABLE I

SHOWING LOOP FORMED BETWEEN STANDS 6 AND 7 OF MILL SHOWN IN FIGURE 4, WHEN 1500-HP. ROUGHING MILL MOTOR HAS SPEED REGULATION OF 5 PER CENT. CALCULATION BASED ON ASSUMPTION THAT DELIVERY SPEED OF STAND 6 WITH STEEL IN ALL ROUGHING STANDS IS EQUAL TO TAKE-UP SPEED OF STAND 7

1. Pass number	1	2	3	4	5	6	
2. Roll diameter, in.	12	12	12	12	11	10	
3. Roll rev. per min. at friction load	42	60	81	120	165	265	
4. Cross section of steel after pass, sq. in. 7.50..	4.45	3.13	2.32	1.57	1.24	.85	
5. Distance to next stand, in.	40.25	44.50	40.25	345.00	304.50	130.00	
6. Volume of steel to next stand, cu. in.	179	139	93	541	378	110	
7. Motor load with preceding stands empty, hp.	1900	1600	1300	1000	700	400	100
8. Delivery speed of stand 6 with preceding stands empty, in. per sec.	130.2	131.6	133.0	134.4	135.8	137.2	138.6
9. Volume delivered from stand 6 with preceding stands empty, cu. in. per sec.	110.7	111.9	113.1	114.3	115.5	116.7	117.9
10. Interval from time piece leaves preceding stand until it leaves this stand, sec.		1.60	1.23	.81	4.69	3.25	
11. Rate of overfeed from stand 6 during interval (10), in. per sec.		1.4	2.8	4.2	5.6	7.0	
12. Amount of overfeed, in.		2.24	3.44	3.40	26.20	22.75	
13. Total accumulated excess strip between stands 6 and 7, in.		2.24	5.68	9.08	35.28	58.03	
14. Take-up speed of stand 7, in. per sec.	110.7	110.7	110.7	110.7	110.7	110.7	

of the mill. However, in the case of the mill shown by Fig. 6, there is a continuous overfeed as soon as the steel enters the second section of the mill. The loop steadily increases and the total length of excess material is directly proportional to the length of billets being rolled.

From the foregoing, it is seen that the speed regulation of motors on individual stands need not be excessively close. On motors driving several stands, good speed regulation is of relatively more importance. However, such drives are usually applied on the roughing stands where the length of piece is comparatively short and rolling speeds low so that loops are more easily taken care of. On most mills, the author believes that motors with as much as 4 or 5 per cent speed regulation will operate successfully, although certain types of mills may require motors of 2 per cent or less regulation.

D-c. motors are ideally suited to the drive of such tandem mills. Speed ranges of 2:1 or greater can be secured by shunt field adjustment. The number of speed points is limited only by the design of the field rheostats, and by the use of coarse and fine adjustment rheostats, each having 100 or 120 points, the total number of settings may be 1000 or more. The inherent speed regulation of shunt or lightly compounded motors can usually be kept within 3 or 4 per cent, over a speed range of 2:1, and by the addition of simple auxiliary equipment the regulation can be maintained as low as 1 per cent.

Compensating pole face windings are used to minimize the effects of armature reaction and thus make the speed drop proportional to the load. The speed curve of a shunt wound machine is usually slightly rising with load, so that a light series field is necessary to produce a flat or slightly drooping characteristic. The amount of series excitation required at full field speed with maximum shunt field excitation is different from that required with weakened shunt field. Therefore, to maintain good speed regulation over the entire speed range, it is necessary to vary the series excitation. On some machines this was accomplished by means of series field shunts and one or more switches to cut the shunts in or out of circuit.

More recently, the series excitation is furnished by a "series exciter," which is excited by the motor armature current, thus giving the same effect as a series winding on the motor itself. A rheostat in this excitation circuit is mechanically coupled to the main shunt field rheostat. Both rheostats are thus operated together and resistance values are so proportioned that the proper compounding is secured for each speed setting. Table II shows the almost negligible speed changes from no-load to double load of a 2500-hp. 160/320-rev. per min., 600-volt motor. Six of these motors are used to drive the intermediate and finishing stands of a modern continuous mill recently placed in service in the Chicago district. The first such in-

TABLE II
SPEED REGULATION OF 2500 HP., 160/320 R. P. M., 600 VOLT,
3360 AMPERE, INDIRECTLY COMPOUNDED, DIRECT-
CURRENT MOTOR

1	2	3	4
Armature amperes	Bus volts	Shunt field amperes	R. P. M.
100	600	35.8	160
1680	600	35.8	160
3360	600	35.8	160
5040	600	35.8	160
6720	600	35.8	159
120	600	19.2	210
1680	600	19.2	210
3360	600	19.2	210
5040	600	19.2	210
6720	600	19.2	210
140	600	14.0	265
1680	600	14.0	265
3360	600	14.0	265
5040	600	14.0	264
6720	600	14.0	264
180	600	10.8	320
1680	600	10.8	320
3360	600	10.8	320
5040	600	10.8	320
6720	600	10.8	319

directly compounded equipment was placed in service in November 1926, and there are now installed or building 46 motors totaling over 60,000 hp., to be used on eleven different mills.

Alternating current adjustable speed motors may be made to have a speed regulation sufficiently low for the successful operation of some tandem mills, and there is a number of mills so driven. However, most tandem

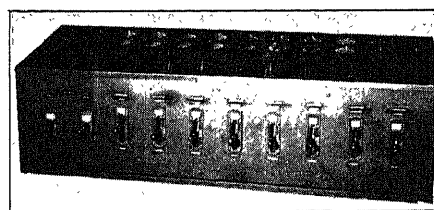


FIG. 7—DESK FOR THE CONTROL OF EIGHT MOTORS AND THREE GENERATORS ON 10 IN. STRIP MILL

mills require several drives, and if d-c. motors are used power can be supplied from a few large motor generator sets or rotary converters, while with a-c. drives a separate regulating machine is required for each motor. Under such conditions, the total cost of a d-c. installation may be as low as that with a-c. drives. This, with the undisputed advantages of simplicity, flexibility, and easy operation, has been responsible for the large proportion of tandem mills driven by d-c. motors.

POWER REQUIREMENTS

Tests have been made on many of the mills now in operation, so that the energy consumption and capacity of driving motors for any proposed new mill may be estimated with considerable accuracy.

Table III shows a power calculation for a thirteen

mill, rolling 3 in. thick billets to strip varying from 0.049 in. to 0.240 in. thick. Results shown in column 14 were calculated using unit energy consumption values read from the lower curve on Fig. 8.

The other method of calculation is based on the energy required to elongate a unit volume or weight of steel, assuming the initial elongation before starting to roll as one. The curves shown in Fig. 9 are plotted from the same test data as Fig. 8, and results in column 19 are calculated from values read from the lower curve.

The results by the two methods of calculation check closely, and such calculations enable the designer to quite accurately select motor drives for a similar proposed mill, although the data must be used with care, and due regard given to the effect of variable conditions, such as mill layout, rolling speed, temperature and analysis of steel to be rolled, percentage reduction per pass, etc., any or all of which may materially influence the power requirements. For instance, the effect of the carbon content of the steel is shown by the curves, the lower curve on each of the figures showing energy consumption for "soft open hearth" steel, with carbon up to about 0.15 per cent and the upper curve showing energy consumption for rolling steel with about 0.60-75 per cent carbon, and 0.50-70 per cent manganese. The high carbon and manganese steel requires over 30 per cent more total energy to reduce to 16 gage strip than does the soft steel.

CONCLUSIONS

The paper indicates that the tandem type of mill with individual stands separately driven by adjustable speed motors has great flexibility and is capable of rolling large tonnages, with very low labor operating costs. A-c. equipment may be used for drives, but d-c. motors are in general more simple and have better characteristics, and where several drives are installed the cost may be as low or lower than for the a-c. drives. Test data from existing mills are available, and power requirements of any proposed mill may be quite accurately estimated and correct applications of driving equipment made.

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5. "Adjustable Speed Drives for Rolling Mills," by L. A. Umansky, *Iron and Steel Engineer*, September 1924, pp. 515-532.
6. "Electric Drive for Ten-Inch Strip Mill at the Laclede Steel Company," by A. F. Kenyon, *Electric Journal*, June 1927, pp. 312-317.
7. *Power Requirements of Rolling Mills*, by Wilfred Sykes, A. I. E. E. TRANS., 1912, Vol. XXXI, Part II, pp. 2051-2066.

Discussion

Fred Butterfield: We have a thing that was not mentioned in the paper, namely, a split bus which helps us out on overloads on one end of the mill or the other, using two generators.

We need close regulation,—5 per cent is not satisfactory. We have had the mill up to 2300 ft. per min., delivering a piece at the finish that was sixty times as long as when it entered the furnace, and when you consider more than 2 per cent of 2300 ft., you will see what it will do with only 16 ft. between the last two stands.

Our problems are fully as much operating as they are engineering, and I do not believe this is the place to discuss them.

L. P. Staubitz: We happen to be one of the mills that require 2 per cent regulation. I agree with Mr. Kenyon that there are many applications where close regulation might not be so essential as it is in our particular application, but I feel that if they could produce a motor which would give absolutely flat regulation, even in mills where it is not essential, it would be better for the operating men.

Mr. Kenyon mentioned the difficulty we had, at first, with the speed. Now, that is particularly true in the finishing stands, because of the short distances we have between them.

Mr. Butterfield mentioned the split bus, and Mr. Kenyon spoke of the speed change between stands 6 and 7. We found that we were able to overcome much of this difficulty at times when we could tie the busses together. Whenever possible we attempt to carry the two busses in parallel. The motor operates from no load to full load in parallel, which was a point somewhat doubtful in our minds at the time when we were first considering the installation.

The motors of the Laclede steel plant are smaller than those of West Leechburg. That is largely due to the fact that in the Laclede plant the main mills have roller bearings, while the other mills have ordinary bearings.

We found that this mill when shut off, when it was originally driven with a-c. motors, would coast, due to these roller bearings, some 12 to 15 min. The old mills ran only about 6 or 7 min. and stopped. In steel-mill operation we often have to stop, and one of the advantages of using d-c. equipment is that, through the use of regeneration in stopping, we are able to bring this mill to a complete standstill in 45 sec.

W. M. Ballenger: Modern tandem or continuous mills, as designed by the mill builders, are such that a wide variety of products must be rolled. This means that the finishing stands must have reasonably good speed regulation and must operate through a comparatively wide speed range.

Since power is practically always brought to the motor room in the form of alternating current at some convenient voltage as 2200 or 6600, it is advisable to use a-c. motors wherever possible in order to get around the losses in conversion apparatus.

If the roughing and intermediate stands can be grouped into trains, large a-c. motors of the induction or synchronous types can be used to advantage. Synchronous motors are becoming more and more popular, wherever applicable, because of their ability to improve the inherent low power factor of steel mills.

On the finishing stands, because of the diversity of products to be rolled, adjustable-speed motors are practically always required. Where extremely close speed regulation is unnecessary, the speed range is not too great, and the motors required are of comparatively large size, induction motors employing either the Scherbius or Kraemer systems of speed control may be advantageously applied. Where extremely close speed regulation and a very wide range of speed are necessary, d-c. motors are almost invariably used. In instances where the adjustable-speed motors are to be relatively small it is usually better to use d-c. machines.

A. F. Kenyon: Mr. Butterfield has mentioned the use, at the Laclede mill, of a split bus. In this case, the supply for the

five motors consists of two 1250-kw. generators, one generator supplying one bus from which is fed the 1500-hp. roughing-mill motor, and the other generator supplying a second bus which supplies the four finishing-mill motors. If desirable, the two busses can be connected together and the generators operated in parallel.

Mr. Staubitz has mentioned that the split bus enables them to increase the range of operation of their mill. There are times when it is desirable to operate the roughing-mill motor at reduced speed, which can be done by running it below 600 volts, while the finishing-mill motors are operated at the full voltage; other schedules require the opposite, full voltage on the roughing and reduced voltage on the finishing-mill motors. The split bus, undoubtedly, has added to the flexibility of this mill.

Mr. Staubitz has also pointed out that some difficulty is experienced in operating the mill with the bus split. The speeds of the motors depend not only on their inherent regulation, but also directly upon the impressed voltage. That brings up a point which I did not mention before, and which I have noted in a

number of mills. The main motors are often supplied with 600-volt power from special generators, while the edging machines between the various stands of the main mill are operated from a shop supply of 250 volts. Naturally the 250-volt and the 600-volt supply sources are not tied together in any way, and considerable difficulty is experienced, due to the edging motors and the main motors changing speeds unevenly with voltage changes on either bus.

The use of roller bearings on mills is a comparatively recent development, and mills using such bearings have not been in operation a sufficient length of time to obtain any great amount of operating data. It is quite generally believed, however, that the use of such bearings will reduce the power demand of the mill to a very considerable extent.

Mr. Ballinger has mentioned that some mills can make use of a-c. drives. I agree with him perfectly, and my remarks in that connection were general only, and any proposed installation should be given individual attention before making a decision for or against any one type of drive.

Demand Metering Equipment Its Application in Recent Developments

BY STANLEY STOKES¹ and LESLIE V. NELSON¹

Member, A. I. E. E.

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Synopsis. Public utilities having to do with supplying electric power are continually finding themselves confronted with problems a little different from anything in the past.

New interconnections of superpower plants and transmission lines often present involved metering installations. The installation described herein has to do generally with such a condition and, specifically, has to provide for metering the simultaneous composite demand of an ultimate installation of 48 separate feeder circuits.

It is believed that this is the largest installation of its kind so far attempted. The importance of this particular job required a very

exacting study of all factors and the operating results, to date, seem to bear out the solution. A novel scheme has been incorporated in the daily routine of handling the demand meter tapes. A general description of this is given. A few details of the physical installation are cited, which show the extreme care used through the whole installation.

While this application is specifically designed for metering, the principles involved are applicable to numerous other uses, some of which are mentioned.

* * * * *

THE expansion of modern superpower systems through involved interconnections and remote points of metering has created situations requiring special adaptations of existing apparatus and distinct development in many of its parts. It will be the purpose of this paper to treat in detail a specific metering problem which was encountered, to giving a description of the apparatus selected and the reasons justifying this particular solution. It is felt that this solution is one which will apply to an increasing number of public utilities confronted with identical situations. At the same time it may be suggestive to others, for the apparatus has a wide use in problems dealing with time studies.

Certain electric power contracts were negotiated during 1927 whereby the entire output of the Cahokia Plant of the Union Electric Light & Power Co. of Illinois would be sold directly to three customers on a combined demand and energy basis. This required that each customer be metered for the maximum demand of his load in kilowatts and his total monthly consumption of kilowatt-hours. The maximum demand was defined as the integrated average load for that fifteen-minute interval in which the greatest total number of kilowatt-hours is taken. All three customers were to be metered in like manner.

The Union Electric Light & Power Co. is supplied entirely with its 60-cycle requirements from Cahokia by means of some 30 submarine cables, crossing under the Mississippi River and terminating in distribution substations located at various load centers throughout the city of St. Louis. The ultimate development of Cahokia provides for 48 such cables, each radiating from the generator bus through its individual oil-circuit breaker. The existing installation of 30 cables comprises three distinct capacities, *i. e.*, 3000-, 7500-, and 12,000- kv-a. per feeder.

1. Both of the Union Electric Light & Power Co., St. Louis, Mo.

Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.

This particular problem obviously becomes that of metering an ultimate of 48 individual circuits simultaneously, and of totalizing the demands of the different capacity cables in such a way that they will all have the correct effect upon the instruments.

The other two customers, namely, the Illinois Power & Light Corporation and the Union Electric Light & Power Co. of Illinois, are supplied by means of the new Cahokia transmitting substation, which has been constructed to step up the energy from 13,800 to 69,000 volts. A portion of the load is transmitted four and a half miles over a common line, known as the Cahokia-Venice Transmission Line, to the Venice Substation, where the Venice Power Plant is tied in and used in times of emergency for relay service. Two lines emanating from this substation, one to Alton and the other to Stallings, supply a part of the load to these two customers. A third line, extending directly from the Cahokia Substation to Belleville, supplies the remainder of the load of the Illinois Power & Light Corporation. The general arrangement of circuits is shown in Fig. 1.

Another clause in the contracts specified that all energy be metered at the generating-bus potential, that is, 13,800 volts. All meter readings must consequently be referred to a common voltage in order properly to assign transmitting and transformation losses to the individual. This necessitates high-voltage metering of the two customers' individual lines before they join into a single circuit. Both high- and low-voltage metering was installed at all points indicated on Fig. 1 without involving any special study. Readings from the high-tension meters would provide the necessary ratios for dividing the readings of the low-voltage meters registering joint use.

No attempt was made to meter these two customers at one point, for it was recognized that this method would involve more unreliable elements than by diverse metering and monthly calculations. Local factors largely decided this point. Thus the second problem was solved in a simple manner, as to meter require-

ments. It will be touched on again, under billing procedure.

A survey of the market, for a solution of the problem of metering the 48 circuits of the Missouri Union Co., was somewhat disheartening. No simple solution was available. A study of totalizing watt-hour meters was made. It was found that these were available in capacities up to, and including, eight circuits but when applied to a 48-circuit problem they became prohibitive in cost.

Further study indicated that a simple watt-hour meter equipped with a standard device for making contacts for the pre-determined passage of a definite amount of energy would be the cheapest, and yet most reliable, solution, providing a means could be found of collecting these contacts from the watt-hour meters on the 48 circuits.

Two distinct methods seemed possible. The first

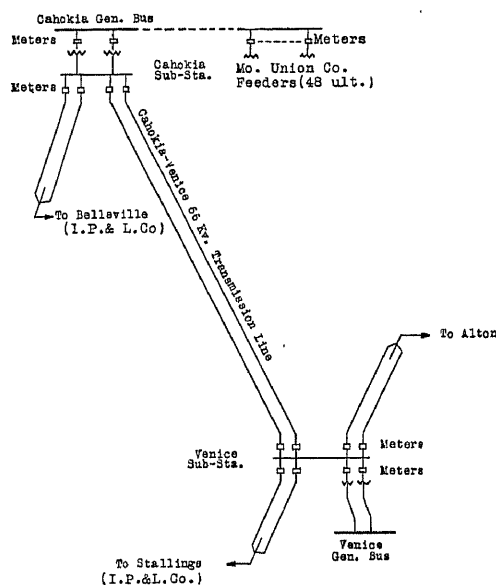


FIG. 1—DIAGRAM OF CUSTOMER CONNECTIONS

scheme suggested that some means of collecting the contacts at definite regular intervals could be developed. This, in principle, would operate like an electric adding machine. The pressing of several keys would correspond to the making of contacts on several of the watt-hour meters. Periodically, the group would be totalized as one presses a totalizing key on an adding machine. The time interval between collection of contacts would have to be less than that required for the making of two successive contacts on the watt-hour meter under greatest load. Simplicity and low cost would obviously obtain with this method. This principle had the disadvantage that if a contact on a watt-hour meter should "freeze" or stick, a contact would be transmitted to the printing demand meter at each collection interval. Thus, evaluating the contacts in terms of kilowatts would give an excessive demand reading and thereby penalize the customer. It was felt that any possible chance of error or trouble in the

metering device which could be guarded against should be resolved in a manner favorable to the customer and thus preserve his good will. This method, while it would incorporate novel mechanical and electrical features, had a further limitation in its inability to register all impulses when there was a large number of watt-hour meters to be totalized. This principle incorporated a piece of equipment which would be required to operate continuously and, thereby, be subject to appreciable wear. In view of these facts it was found advisable to discard this method in favor of the second, which will be described at length.

The second possible method provided that the contacts from the watt-hour meters be collected and recorded on a demand meter at the instant that they were made. With a multiplicity of meters, such as 48, the probabilities were that frequently several contacts on separate meters would occur simultaneously. Some means of absorbing these contacts at the instant of making and of giving them out uniformly for registration was, of course, necessary so that none would be lost in the process. This principle involved no such limitations as were encountered in the first method. Any number of circuits might be totalized by simply pyramiding the recording instruments. It also had the advantage that the recording instruments were operating only at the time that watt-hour meter contacts were made. At times of no load on the circuits there would be no wear and tear on the recording instruments.

These fundamental considerations seemed to be provided in a totalizing relay on which the manufacturer agreed to make certain necessary modifications in his standard equipment to meet our specifications adequately. By means of the instruments shown, and the schematic diagram of connections (Fig. 2), the general principle of operation may be followed. By passing an electric current through a watt-hour meter the element is made to revolve, thereby driving the contact device which makes and breaks a circuit at intervals proportional to the loading of the watt-hour meter. A contact impulse emanating from a watt-hour meter must obviously be evaluated in terms of kilowatts before it leaves the meter. This is accomplished by making the gearing and number of cam teeth within the watt-hour meter proportional to the kilowatt constant of the meter itself. After a contact has been imparted to a totalizing relay it loses its identity and value in relation to other contacts. Tracing this contact circuit (Fig. 2), we find that a coil, *A*, is energized in a totalizing relay which actuates a rocker arm and, by means of a ratchet device, *D*, advances a shaft a definite number of degrees. Simultaneous contacts on two adjacent coils (not shown) are made effective through differential gearing, *E* and *F*. A contact is then transmitted through successive stages of gearing to a coil spring between gears *H* and *K*. This spring functions to store several contacts if they occur simultaneously, and, by un-

winding, revolves shafts *I* and *N* at a uniform rate, thereby giving out the same number of contacts as was received. The driven shafts are damped in their rotation by means of a disk and magnet. This final shaft, *I*, has two cams, *L*, and contact devices on it, so that its rotation is translated again into contacts which are recorded on a printing type of demand meter. Stops on the gears, *H* and *K*, on each side of the coil

connected to a coil on an 8-circuit totalizer, which has been designated the master totalizer. The impulses emanating from this master totalizer are recorded on a standard printometer. The 15-min. interval specified by contract for demand readings is obtained through clock-driven contacts which reset the printometer to zero reading every fifteen minutes.

Each 6-circuit totalizing relay has a contact ratio of

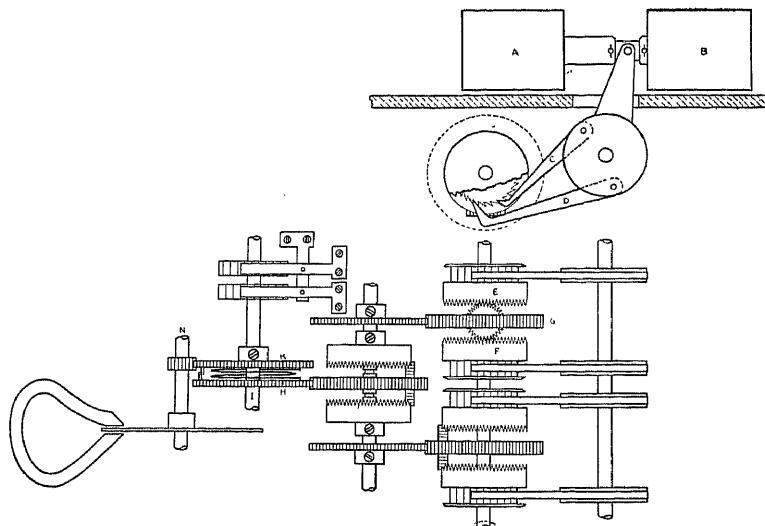


FIG. 2—SCHEMATIC DIAGRAM OF FOUR-ELEMENT TOTALIZING RELAY

spring prevents over-registration of the relay. The use of double-contact devices instead of single is especially noteworthy. Each set of contacts is connected to two coils which work against each other. Once a contact is made and its coil energized, further

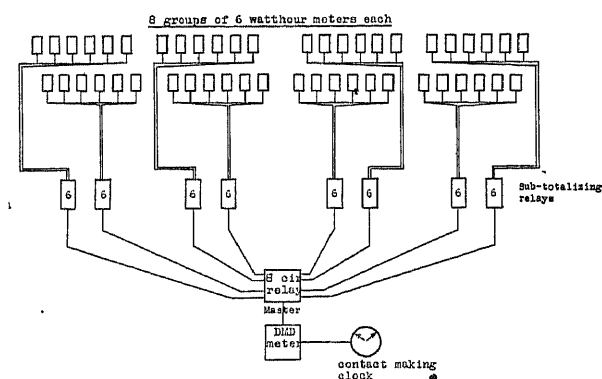


FIG. 3—SIMPLIFIED CIRCUIT LAYOUT FOR 48-CIRCUIT TOTALIZING DEMAND METER

successive contacts on this one circuit—such as is caused by chattering—have no effect until the other contact functions. This description covers the general operation of a single totalizing relay. By pyramiding these relays, as shown in Fig. 3, practically any number of circuits, or contacts, may be recorded.

The 48-circuit installation comprises 8 six-circuit totalizing relays which are designated as subtotalizers. The contacts on each sub-totalizing relay are, in turn,

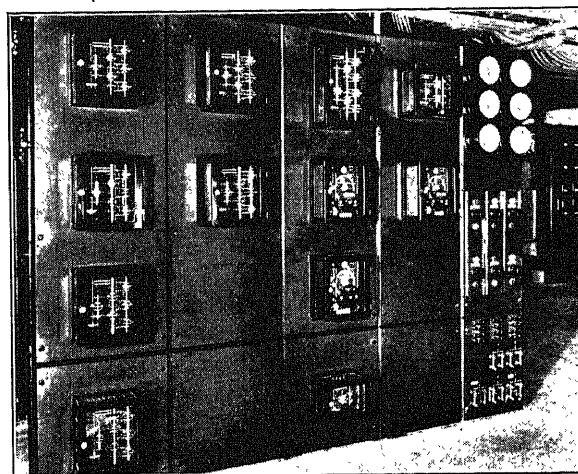


FIG. 4—FRONT VIEW OF 48-CIRCUIT (ULTIMATE) TOTALIZING DEMAND METER INSTALLATION, —CAHOKIA PLANT

five to one, *i. e.*, for every five impulses received, it gives out one to the 8-circuit master totalizer. The 8-circuit totalizer also has a contact ratio of five to one, giving only one contact to the recording printometer for every five received from the subtotalizers. As an example, assume that the printometer registers 150

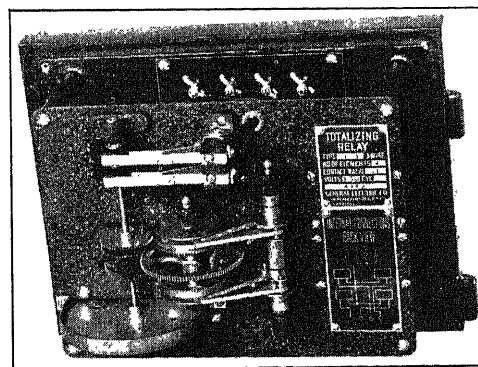


FIG. 5—TYPE DT-1 TWO-ELEMENT TOTALIZING RELAY, FRONT VIEW WITH CASE REMOVED

contacts; this means that the 8-circuit relay has received 750 contacts in the 15-min. interval. On the average, each 6-circuit totalizer must have contributed 93.7 contacts and received 468.7 contacts from the 6-watt-hour meters connected to it. There being eight groups of watt-hour meters, a total of 3750 contacts must have been made in the watthour meters in the 15-min. interval. Each watthour meter, on the average, could have contributed 78.1 contacts per 15-min. interval, or 5.2 contacts per minute if all were evenly

loaded and of the same capacity. With a permissible shaft speed on the watthour meter of 30 rev. per min. it would take slightly less than six revolutions of the watthour meter shaft to give one contact, or approximately one contact for each 12 sec. elapsed. This particular installation has a constant of 2000 kw. per contact as registered. With a maximum scheduled number of contacts of 150 this would indicate a customer demand of 300,000 kw.

It would be folly to expect perfect operation in this type of equipment in spite of the high standards of manufacture. In an attempt to guard against errors of registration it was specified that each individual totalizing relay should be equipped with a cyclometer so that the total number of impulses, received by the totalizer from the group of watthour meters connected to it, could be ascertained and checked periodically. The readings of the cyclometer dial when compared with the summation of the readings of the respective registers

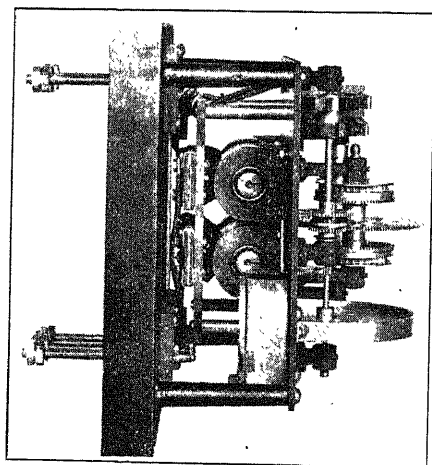


FIG. 6—TYPE DT-1 TWO-ELEMENT TOTALIZING RELAY, SIDE VIEW WITH CASE REMOVED

on the six watthour meters, connected to it, should check. Any failure of these figures to check very closely *i. e.*, within a tenth of one per cent or thereabouts, would indicate a faulty contact mechanism on one of the 6 watthour meters. Periodic checking in this matter affords a simple means of locating and correcting any such troubles before they can become accumulative. The reading of the cyclometer dial on the master totalizer, over a period of a month, will also indicate the total kilowatt-hours supplied to the customer over the 48 circuits for the entire month. This saves considerable time at the end of the month when there is always a large amount of detail reading and checking. The daily checking of the cyclometers renders this figure accurate for use.

Meters and relays of this type, because of their inherent points of design, are fundamentally foolproof. They do not require the manufacturing precision of a delicate watch mechanism or a high-grade clock. The laboratory methods used in checking, adjusting, and calibrat-

ing these instruments assure us of a high grade solution of this particular problem. Such a metering installation, upon whose readings millions of dollars are paid out annually, must be stable and reliable to justify the confidence of all concerned.

Fig. 4 shows the front view of the installed metering

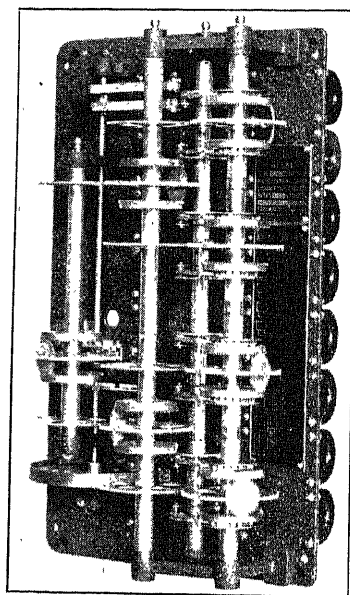


FIG. 7—TYPE DT-1 EIGHT-ELEMENT TOTALIZING RELAY FRONT VIEW OF MECHANISM, REMOVED FROM CASE

panels. The wiring on the back of the panels is continuous from the contacts in the watthour meter to the

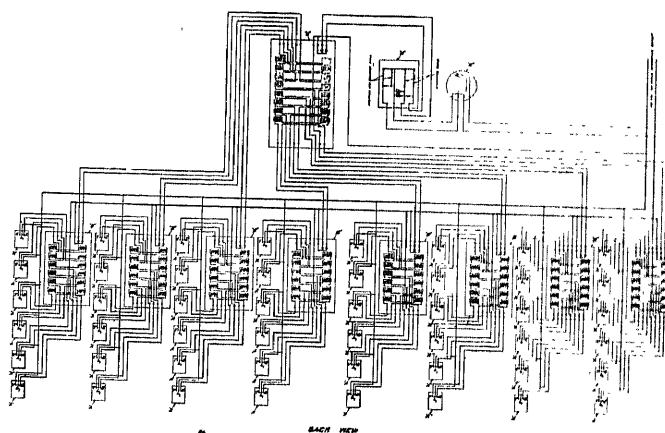


FIG. 8—WIRING DIAGRAM OF TOTALIZING RELAY SYSTEM FOR OBTAINING THE SIMULTANEOUS DEMAND ON 48 METERED CIRCUITS

coil in the totalizing relay. No joints or splices have been tolerated and, therefore, it is expected that contact troubles which ordinarily occur in small current circuits will be eliminated.

Two- and four-circuit totalizing relays (Figs. 5, 6, 7) are used in similar fashion for metering the service to the Illinois Power and Light Corporation and the Union Electric Light and Power Company of Illinois. No

special detail of the installation features for these two customers will be mentioned. Their problem is solved primarily by methods of computation and billing.

The contractual relations of the three customers are all predicated upon a service-at-cost arrangement. This imposes a relative value on the demand and energy usage of each customer with respect to the others. From this point of view, the distribution of losses and costs presented a unique problem which has been simply solved.

The printed records, which are taken daily from the demand meters, are in the form of narrow tapes. These are collected daily and pasted in columns on a printed form. The readings on each tape are evaluated in

very convenient method for filing the tapes for future reference.

The demands for equipment of this nature are, at present, quite active, and there is a certainty that these demands will increase as industrial plants grow and take energy from more than one service connection. As other power systems become interconnected simultaneous demands taken at widely separated points will be totalized. In many cases these impulses may even be transmitted over telephone lines and registered at a common point. This eliminates the necessity for synchronized clocks to assure that the same 15-min. interval is registered on all meters when located at diverse points.

The use of the totalizing relay is not necessarily confined to the summation of electrical units but, on the contrary, it may be successfully employed for numerous applications; for example, totalizing the number of street cars which pass certain points at a given interval, or for determining the operations in the manufacturing plant. It is only necessary to provide contacting devices for the specific application to open and close the required number of circuits.

The speeds of operation of the relays and demand meters are, of course, a limiting feature. But this can always be provided for, in some manner or other, through suitable gear ratios.

Wiring in this type of installation is extremely simple, as may be seen from the wiring diagram shown in Figs. 8 and 9. No long secondary leads from current transformers are necessary. All wiring which interconnects the pieces of apparatus carries only the small intermittent currents necessary to operate the relay coils. These currents are of the magnitude of milliamperes. The described installation is a composite of both d-c. and a-c. instruments operating on 60 cycles, 130 volts, and, from operating experience to date, would indicate equal reliability with either method. Any combination of d-c., 60-cycle or 25-cycle circuits may be totalized into one composite demand. This feature will, no doubt, find considerable application to customer services, where, due to changes, he finds himself confronted with the necessity of accepting both 25- and 60-cycle power from the local utility.

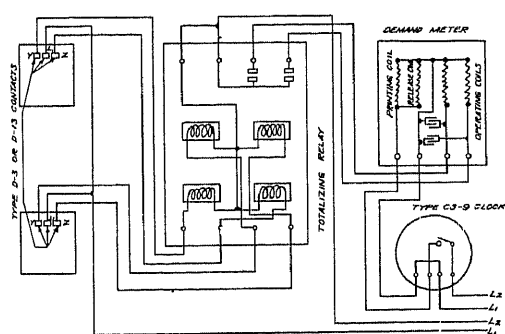


FIG. 9—CONNECTIONS OF TYPE PD DEMAND METER, TYPE CS-9 CLOCK AND TYPE DT 2 CIRCUIT TOTALIZING RELAY TO MEASURE DEMAND ON 2 METERED CIRCUITS. OPERATING CIRCUIT 110-220 VOLTS, ALTERNATING OR DIRECT CURRENT

terms of kilowatts for each 15-min. interval. By direct reference along a horizontal line the demands of an individual customer for any particular interval may be obtained. Similarly, the demands of the other customers at this, or other, times may be obtained by selection. As was mentioned earlier, high-tension (66-kv.) metering is used for the distribution of energy where customers are served over common sources of supply. Ratios are obtained from these figures, which are used in connection with the low-tension readings, for the distribution and assignment of losses. Customer load curves may be plotted directly from the readings on these charts. At the same time, this provides a

The Impedance Relay Developments and Application

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and

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Synopsis.—This paper reviews the developments made in the impedance relay since its introduction in 1923. A brief review is given of its construction and operation. Special emphasis is placed on the methods of obtaining proper potential for the restraining elements without the use of high-tension potential transformers. The use of potential from condenser type bushings is discussed.

To make possible the use of low-tension potential, methods of compensating for the voltage drop through power transformers and for the shifting of the secondary neutral point have been developed. These methods are described. Some special applications of the relay are also discussed.

* * * * *

SINCE the impedance relay was first described in an Institute paper in 1923² a large number of them have been applied to transmission systems both in this country and abroad. The increasing size and complexity of systems due to the many interconnections being made is responsible for the increasing use of this relay. The use of the former methods, involving over-current and directional relays, is difficult in interconnected systems having several generating stations, some of which may operate only a part of the time. In systems of this sort, the changes in direction and magnitude of the fault current may entirely ruin the selective current and time settings used with over-current and directional relays. The former protective schemes also become undesirable even on systems comparatively simple but having a number of stations in series. This is due to the fact that the relays have to be given graded time settings, which are a minimum at the end of the loop or line and which increase at each station as the generating station is approached, with the result that the most severe faults, (those occurring near the generating stations), are left on the system, sometimes for several seconds. With high standards of service to be maintained such a condition is most undesirable.

On existing systems confronted with the problem of demands for better service or the building of additional stations, considerable benefit may be derived by placing the impedance type relay at the generating station and stations nearby, without rearranging the whole protective system.

During the past few years a great many improvements in the relays have been made which have greatly widened its field of application. Some of these improvements have been described before,³ but for the sake of completeness they will be mentioned in this paper. Much experience has been gained in the

application. The difficult and important problems of obtaining the necessary potential for these relays has received a considerable amount of attention.

CONSTRUCTION AND OPERATION

The impedance relay is quite similar in appearance to the wellknown induction disk over-current relay, except that a voltage actuated restraining element has been added. The restraining element acts directly on the contact mechanism and is connected to the over-current element through a lever arm and spring. Figs. 1

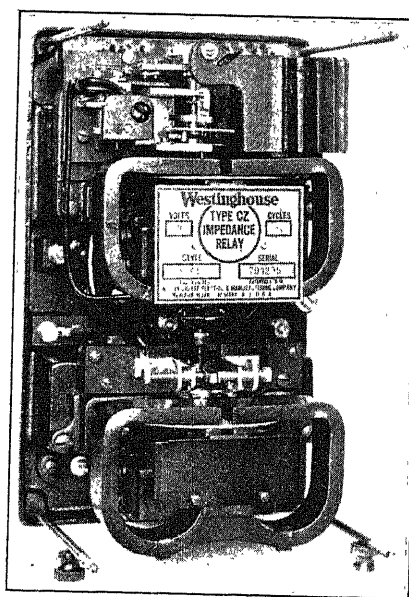


FIG. 1—IMPEDANCE RELAY SHOWING DETAILS OF CONSTRUCTION AND DIRECTIONAL ELEMENT MOUNTED IN THE LOWER PART OF THE RELAY

and 2 show the mechanical features of the relay. When the current in the over-current winding exceeds a predetermined value the disk is caused to rotate. This disk is damped by a permanent magnet so that its speed is approximately proportional to the magnitude of the current. The rotation of the disk winds up the spring, one end of which is fastened to a counter-shaft geared to the disk shaft. A rocker arm pivoted at its center and mounted directly above the disk is con-

1. Both of the Westinghouse Electric and Manufacturing Company.

2. L. N. Crichton, *The Distance Relay for Automatically Sectionalizing Electrical Networks*, A. I. E. E. TRANS., Vol. XLII, 1923, p. 527.

3. "Developments in the Impedance Type Relay." *Electric Journal*, Feb. 1927, J. V. Breisky and H. A. McLaughlin.

Presented at the Regional Meeting of the A. I. E. E. St. Louis, Mo., March 7-9, 1928.

nected to the other end of the spring by means of a lever arm. The rocker arm has the moving contact on one end, and has suspended on the other end the core of the restraining element. The pull of the voltage coil, which opposes the closing of the contacts, is directly proportional to the applied voltage. For any given applied voltage the spring must be wound a definite amount before it will overcome the restraint and close the contacts. The speed with which the spring is wound to this definite amount, is dependent on the magnitude of the current; and since the restraint is directly proportional to the voltage, the time of operation is proportional to the impedance. Then, by properly setting the relays, selective operation may be obtained whereby the relays nearest the fault will act before any others. The time of operation also will be nearly independent of current so that this action will not depend upon the operating conditions as long as the operating point of the relay is exceeded.

In Fig. 3 is shown a family of time-current curves for various voltages.

It will be noticed that where protection against both line-to-line and line-to-ground faults is desired, it is necessary to use two relays per phase, one restrained by a delta voltage and one by a star voltage. This is necessary since either one of these voltages may be reduced to a very low value, by a fault, without re-

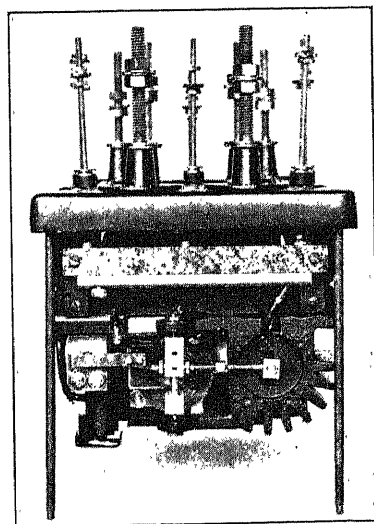


FIG. 2—TOP VIEW OF IMPEDANCE RELAY SHOWING DETAILS OF VOLTAGE COIL AND ROCKER ARM

ducing the other more than approximately 50 per cent. For use in special cases where space is restricted a duplex relay has been developed which combines in one unit two restraining elements operating on the same over-current element.

The ordinary directional element may also be combined with the impedance element to give a relay, which will operate to trip its breaker when the current flow is in a predetermined direction. This directional element is shown in the relay in Fig. 1.

ADJUSTMENTS

There are two adjustments available for setting this relay, a current and a voltage adjustment. The current taps are similar to those on the usual over-current induction relay. Adjustment is made by changing the position of a set screw in a connector block, thus changing the number of turns on the main coil. This fixes the minimum current at which the relay will operate and is determined mainly from a considera-

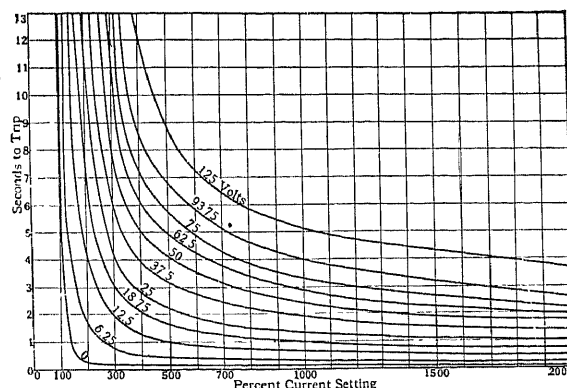


FIG. 3—CHARACTERISTIC CURVES OF 125-VOLT IMPEDANCE RELAY SET ON 125-VOLT TAP.

These curves apply to any voltage tap, if the voltage by which the curve is designated is multiplied by $T_v^2/125$, where T_v is the voltage tap desired.

tion of the minimum short-circuit current existent with a fault on the system. The voltage adjustment consists of inserting resistance in series with the restraining coil in order to cut down the voltage actually applied to the coil. These two adjustments used in conjunction make it possible to set the relay to operate in a short time irrespective of the impedance of the line to be protected.

In the original relay, resistors were included in the relay case, with three voltage taps, similar to the current taps. It was soon found, however, that the range provided by these three voltage taps was insufficient, especially since the current adjustment must be made in such a way that the minimum short-circuit current gives a relay current of at least 200 per cent tap value. This requirement often necessitates the use of the four or five ampere tap, leaving it entirely to the voltage taps to obtain the proper adjustment for a line of high or low impedance.

THE EXTERNAL RESISTOR

In order to get a wide enough range of voltage taps to cover all conditions encountered, an adjustable resistance unit, known as the external resistor, was designed to be used in conjunction with the relay. The latest form of external resistor is shown in Fig. 4. By the use of this resistor and the increased number of current taps, which were made possible by the removal of the voltage taps from the relay case, very accurate settings may be obtained with lines of various lengths and a wide range of short-circuit currents.

The resistor is connected directly in series with the voltage coil of the impedance element. Fig. 5 shows a connection diagram for a simple case of line and ground protection where high-tension potential transformers are used. This diagram shows the manner in which the resistors are inserted in the restraining coil circuits.

DIRECTIONAL CONTROL

One of the most recent improvements precludes the possibility of this relay operating incorrectly on account

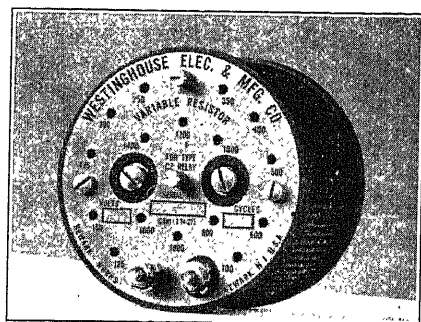


FIG. 4—THE EXTERNAL RESISTOR USED IN CONJUNCTION WITH THE IMPEDANCE RELAY

of sudden reversals of power flow, or a surge of synchronizing power set up in a system when a faulty line is disconnected by other relays on the system. The

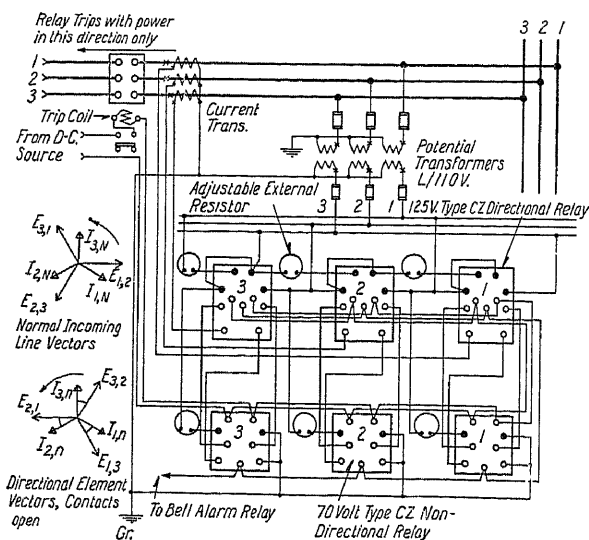


FIG. 5—EXTERNAL CONNECTIONS FOR LINE AND GROUND RELAYS ON A GROUND SYSTEM USING HIGH-TENSION POTENTIAL TRANSFORMERS

operation of the impedance element is controlled by that of the directional element. In other words, the direction of power flow must be in the correct direction for tripping and must remain so for a sufficiently long time for the impedance element to complete its operation before it can close its contacts. Thus, it will be seen that the relay cannot be operated by sudden reversals of power such as will occur during the readjust-

ment of a system when a fault is cleared. It will be noticed that even though these surges should be of considerable magnitude and duration, the restraining action of the impedance voltage immediately becomes predominant after the removal of a fault from the system.

This improvement was accomplished by connecting the directional contacts in the secondary and upper-pole circuit of the impedance element current electromagnet, making it necessary for these contacts to be closed before the impedance element disk can commence to rotate. In order to make this change feasible it was necessary to redesign the secondary winding, so that a sufficiently small current and a high enough voltage would be obtained to prevent any error due to contact resistance. The fact that the directional contacts must close before the impedance element can start to function makes it possible to set them very close without danger of an incorrect operation due to rebound or jarring. How the directional control is

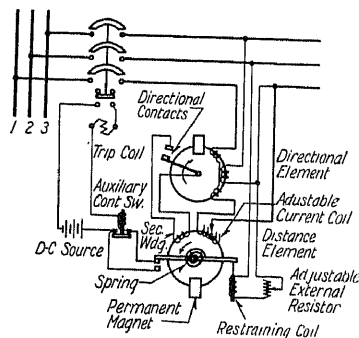


FIG. 6—SCHEMATIC DIAGRAM OF IMPEDANCE RELAY SHOWING DIRECTIONAL CONTROL OF IMPEDANCE ELEMENT

obtained is shown in Fig. 6, the schematic diagram of a relay.

Directional Element. A new directional element embodying several improvements has been developed and will be used in this relay. It can be made to operate with either a 30 or 90 deg. relation between the current and voltage applied to the relay, by not having, or having, a resistor in the potential circuit. This allows the use of the connection best suited to the system condition. Where either might be used, it is sometimes desirable to use the 90 deg. connection with the resistor in the potential circuit, since the volt-ampere burden of this circuit is then reduced. It will be shown in a later section how desirable this is under certain conditions.

VOLTAGE AND CURRENT REQUIREMENTS

In order that under fault conditions, the impedance measuring element at a station shall determine its tripping time according to the impedance of the intervening line between the station high-voltage bus and the fault, it is necessary that this element be supplied with the following quantities:

- a. Current proportional to the line current.
- b. Voltage proportional to the line voltage at the station.

1. Voltage between conductor and ground—for phase-to-ground fault protection.

2. Voltage between conductors—for interconductor fault protection.

Current transformers of the dry type, oil-insulated wound type, or bushing type satisfy the demands for current correctly representative of conductor current, and their application will not be discussed further here.

Sources of Voltage. At stations transmitting at generated voltage there is but one source to be considered, the transmission line itself.

At stations transmitting at other than generated voltage, and at transformer substations, there are, obviously, two main sources of voltage: (a) The high-tension bus, (b) The low-tension bus.

The use of high-tension potential transformers generally insures the delivery, to the impedance relays, of voltages correct in every respect. On very high-voltage lines, the cost of high-tension potential transformers becomes prohibitive and in such cases, other methods by which correct voltage may be obtained become economical. The direct use of low-tension potential transformers will in many cases give incorrect operation. The reasons for this will be pointed out presently.

Potential from Condenser Bushings. Recently a method of obtaining potential from condenser type bushings, (used in circuit-breakers and transformers), has been developed for synchronizing,⁴ which also can be used on extra-high-voltage systems for relaying if the volt-ampere burden is sufficiently low. This method consists, briefly, in using the condenser bushing as a potentiometer to feed a small transformer and a network consisting of a condenser and a reactor mounted directly on the breaker or transformer. In general, a voltage thus will be obtained of sufficient accuracy for relay work. Since the phase position, and not the magnitude of the voltage required for the directional element, is of importance it may be advantageous in certain cases to reduce the burden on the condenser bushings by connecting only the restraining elements to them and obtaining the directional element potential from the low-tension bus.

Use of Potential from the Low-Tension Bus. Under certain conditions, the potential may be taken from the low-tension bus in a transformer station and directly applied to the relay. Generally, however, as pointed out in the next sections, correct operation will not result. To take care of these cases, two systems of compensation have been developed which will allow the use of low-tension potential where this is more economi-

cal than using high-tension potential transformers. The first of these compensating schemes was suggested by several people. The second is the result of S. L. Goldsborough's work. Mr. Goldsborough also did the development work on both types.

FAULTY OPERATION DUE TO FEEDBACK WHEN USING LOW-TENSION POTENTIAL

As an example of a possible faulty operation due to the use of low-tension potential transformers without corrective means, a system involving two generating stations *A* and *B* and a substation *C*, without feedback, (Fig. 7), will be considered and an interconductor fault will be assumed to have occurred close to station *B* at the point *X*. Low-tension potential transformers are shown in use at *B* and *C*. For simplicity high-tension potential transformers are assumed to be in use at station *A*.

Proper relaying would require the isolation of line *AB* by the practically instantaneous tripping of relay No. 1, successfully differentiating with relay No. 3. This should be followed by the tripping of relay No. 4

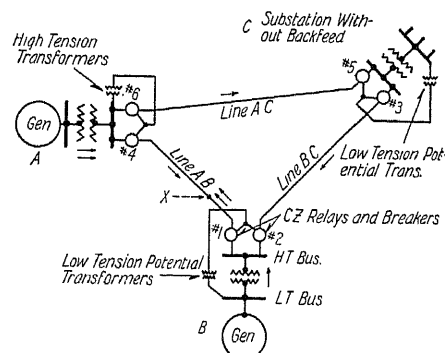


FIG. 7—SYSTEM DIAGRAM USED TO DEMONSTRATE NEED OF COMPENSATION FOR FEEDBACK WHEN USING LOW-TENSION POTENTIALS

within 0.75 sec., successfully differentiating with relay No. 5—the fault current through lines *AC* and *BC* having reversed upon opening No. 1 breaker.

The actual relaying would, however, be as follows: Relays No. 3 and No. 4 would both trip in about 0.75 sec., but relay No. 1 would be greatly delayed, receiving as it does a voltage higher than the drop over the short section of line *AB* to the fault, by an amount equal to the drop over the impedance of the power transformer at *B*—generator *B* being responsible for the current which results in this drop. The net result is the final clearing of the fault, but only after line *BC* has been opened unnecessarily.

The proper application of type *KX* compensators which are described later, would eliminate this incorrect operation due to the use of low-tension potential transformers.

FAULTY OPERATION DUE TO NEUTRAL SHIFT

As an example of faulty operation due to neutral shift, a system involving a generating station *A*,

4. E. E. Spracklen, D. E. Marshall, and P. O. Langguth, *The Use of Condenser Type Bushings in Connection with Synchronizing Equipment*, A. I. E. E. Quarterly Trans., Vol. 47, No. 2, April 1928, p. 684.

(Fig. 8, Part *a*), with high-tension neutral grounded and a transformer substation *B* with high-tension neutral ungrounded will be considered, and a single conductor fault-to-ground will be assumed to have occurred on conductor No. 1 close to station *B* as at the point *X*.

For the sake of simplicity, it is assumed that the fault is a perfectly solid ground and that the voltage at the generating end of the line stays up to full normal value.

In parts *b* and *c* of Fig. 8 are shown, respectively,

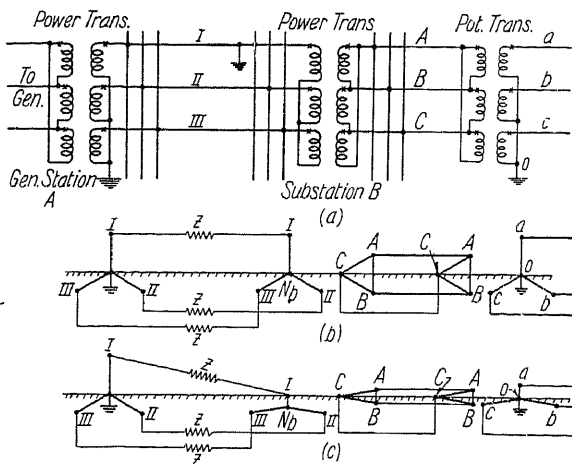


FIG. 8—SYSTEM DIAGRAM AND VECTOR DIAGRAMS.

Showing effect of shift in neutral at an ungrounded substation on a grounded system. Parts *b* and *c* show, respectively, normal vector relations and those existing for the ground fault shown in Part *a*.

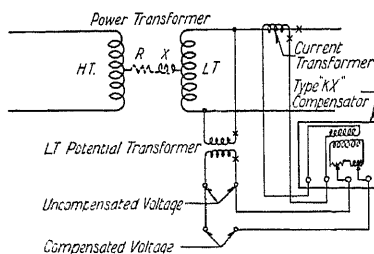


FIG. 9—ELEMENTARY DIAGRAM OF TYPE KX COMPENSATOR APPLIED TO A SINGLE TWO-WINDING POWER TRANSFORMER

the vectors of normal conditions and the vectors for the single conductor fault-to-ground; the vector diagrams in each case being labeled to coincide with the circuit diagram in part *a*.

The second vector diagram in part *c* shows how the star voltages, on the high-tension side of the substation power transformer, rearrange themselves—the neutral point N_B , being free, assumes the new equilibrant position at which the voltage $I N_B$ is 33.3 per cent of its initial value, or 19.3 per cent of the voltage II, III.

Although the faulted conductor is at ground potential, this shift in power transformer neutral results in a voltage *a, o*, instead of zero voltage, being finally made

available for the voltage coil on the ground relay, resulting in delayed operation.

The type KY compensators, the application of which is outlined in a subsequent section, have been developed to compensate for this shifting of the neutral.

TYPE KX COMPENSATOR

Basic Principle. In principle the type KX compensator is similar to the line-drop compensator commonly in use on feeder regulator installations. The KX compensator delivers at its two output terminals a voltage, adjustable in phase position and magnitude with respect to the current supplied to its two input terminals. By means of four dials, coarse and fine adjustment of both in-phase and quadrature voltages are made available, the dial setting being rated in volts for a primary or input current of five amperes. For the purpose of illustration a KX compensator is shown (Fig. 9) as functioning to compensate for the drop over a single two-winding power transformer.

The uncompensated voltage delivered at the instru-

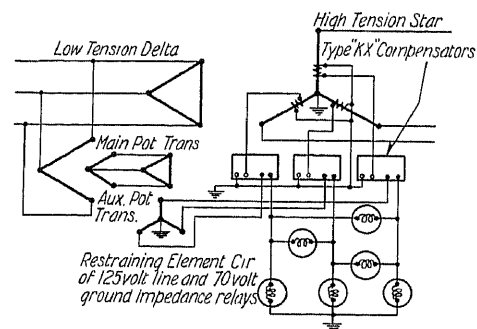


FIG. 10—CONNECTION DIAGRAM SHOWING APPLICATION OF TYPE KX COMPENSATIONS TO A STAR-DELTA CONNECTED TRANSFORMER STATION, WITH NEUTRAL GROUNDED, EMPLOYING LOW-VOLTAGE POTENTIAL TRANSFORMERS

ment side of the potential transformer does not bear a constant relation to the voltage on the high-tension side of the power transformer, being higher or lower than its normal ratio depending upon the direction of power flow through the power transformer. The extent to which it deviates from its proper value is a function of the transformer impedance and of the magnitude of the current flowing through the power transformer winding.

The KX compensator is shown being supplied with current at its input terminals proportional to the power transformer current.

When the compensator dials have been set according to the resistance and reactance of the power transformer, the voltage component representing the drop over the power transformer is accounted for; and a final compensated voltage is made available, which is satisfactory for use on the impedance relay restraining element, as it bears a constant relation to the high voltages and is independent of direction of power flow.

Typical Three-Phase Application—Two-Winding Transformers. The application of type KX compensa-

tor to a star-delta bank of power transformers with high-tension star neutral grounded is shown in Fig. 10. Three compensators are shown, each one serving to compensate for the interwinding impedance of one transformer in the bank.

With the arrangement as shown, compensation is correct for both interconductor faults and conductor-to-ground faults, the particular relay, or relays, actively concerned with clearing the fault being supplied with voltages correctly representative of the conditions on the faulted high-tension side.

Three-Winding Transformers. The method of compensating for the drop through two-winding transformers shown in Fig. 10 can, of course, be expanded to care for three-winding transformers. In this case, where backfeed is possible from both the low and intermediate voltage windings, two sets of compensators and the necessary current transformers to feed them are required. The impedances used in this connection are the equivalent star impedances⁵ rather than the impedances between windings, and thus special requirements are imposed on the location and ratios of the current transformers used.

Source of Current for Compensators and Extent of Protection Resulting. In Fig. 10 the current transformers feeding the compensators are shown located in the high-tension winding. Since the burden imposed by the compensator is too great to be handled by bushing type current transformers, these current transformers would be located in the neutral side of the power transformer windings, in order to avoid the expense of using oil-insulated current transformers in the high-tension leads. It is also possible to place the transformers on the low-tension side. In this case, to get complete compensation, it is necessary to have them inside the delta, that is, one in series with each winding. In case it is not possible to do this they may be placed in the main secondary leads and by connecting the compensators in a different manner correct compensation will be obtained for line-to-line and three-phase faults. Drops caused by circulating currents will not be compensated for and, consequently, improper compensation may result in case of ground faults which cause a circulating current to flow.

Use of Auxiliary Potential Transformers. In the general case the over-all potential transformer connections should be equivalent to the reverse of the power transformer connections. In Fig. 10 the power transformer is star-delta and the potential transformers are open delta plus a delta-star combination, giving a delta-star as the over-all transformation. By this means the set of star and delta voltages produced at the instrument side of the potential transformers are in phase with the particular high-tension voltages to which they are proportional.

The low side of the open-delta main potential trans-

former is a 125-volt delta, but is in incorrect phase position. This condition is common when standard ratio potential transformers are used. The use of a set of auxiliary transformers, preferably of a 1.73 to 1 ratio, permits the use of standard ratio main potential transformers, hence is a matter of real economy and at the same time results in proper phase positions of the final voltages. Auxiliary transformers having a 2 to 1 ratio have been used resulting in a final delta of about 100 volts; but the 1.73 to 1 ratio is preferred, on account of the fact that through the use of the 2 to 1 ratio the length of the shortest line that can be protected is somewhat increased.

In certain cases where it would be possible to get the proper voltages by the use of three main potential transformers it may be more economical still to use the main transformers connected open delta and a set of auxiliary transformers. This will, of course, depend entirely on the primary voltage of the potential transformer.

THE KY COMPENSATOR

The KY type compensator has been designed to nullify the effect of the shift in the neutral, which takes

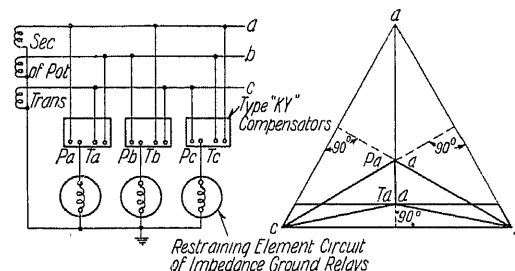


FIG. 11—PART a. CONNECTION DIAGRAM SHOWING APPLICATION OF TYPE KY COMPENSATORS. THIS DIAGRAM IS A CONTINUATION OF PART a OF FIG. 8

PART b. VECTOR DIAGRAM SHOWING THE UNCOMPENSATED AND THE COMPENSATED VOLTAGE VECTORS

place on the ungrounded star high-voltage side of the power transformer bank at a substation on a grounded system, thereby permitting the use of low-tension potential transformers at such stations.

In principle the KY compensator is similar to the KX compensator, except that it is a potential device. The KY compensator delivers at its two output terminals a voltage which for the general setting is 19.3 per cent of, and in quadrature to, the voltage impressed across its two input terminals.

When three such devices are connected, as shown in part a of Fig. 11, (in which the potential transformers secondaries are the same as those shown in Fig. 8 part a), the undesirable voltage a, o shown in the last vector diagram of part c of Fig. 8 (and shown on a larger scale in Fig. 11 part b), is completely nullified, resulting in zero voltage being delivered to the relay as is correct for the particular fault described. The voltage P_a, T_a

5. J. F. Peters, "Three Winding Transformers," *Electric Journal*, January 1925.

combining with the voltage a, o produces voltage T_a, o (zero volts) which is correctly representative of the actual faulted conductor voltage above ground at the time of the assumed dead fault-to-ground.

For ground faults which do not result in zero voltage at the point of fault it can be shown that the KY compensators still function correctly, in that the voltage delivered to the active relay bears the same ratio to the voltage it is to represent as it does under normal operating conditions. Normally, when using type KY compensators, the restraining elements of the impedance ground relays receive a voltage equal to two-thirds of the full star voltage. The fact that the above mentioned ratio is the same under all fault conditions permits correct operation to take place, the existence of the two-thirds ratio being taken into account in setting the impedance ground relays when associated with type KY compensators.

SPECIAL APPLICATIONS

On some grounded neutral systems the current caused by an accidental ground may vary over wide ranges, due either to operating or soil conditions. The use of impedance ground relays in conjunction with a directional ground relay operating on residual current and voltage, which can be made sensitive since it is independent of load current, offers the advantage of providing fast clearing of heavy grounds by the impedance relay and the slower, but still selective clearing of the low-current faults by the more sensitive residual directional relays having graded time settings.

In some systems, due to the long lines and the small amount of generating capacity on the system during certain periods, the minimum short-circuit current may be less than the maximum full-load current. For use on such systems an impedance relay having low-current taps (used in conjunction with a fault detector), has been developed. Under normal conditions, the impedance relay is kept deenergized. On the occurrence of a fault, the fault detector makes the impedance relay operative and it tends to operate the breaker in accordance with the distance from the fault. The fault detector is responsive to an overcurrent or an undervoltage of predetermined values, all faults being accompanied by one or the other of these conditions.

CONCLUSIONS

The impedance relay, while it is relatively new in the field of protective relays, is already being used quite extensively both in this country and abroad. Because of the impossibility of obtaining satisfactory results with overcurrent and directional relays in many cases, and the objectionable time delays involved even when selectivity can be obtained, the impedance relay is receiving more and more consideration. This is a step in the right direction since the impedance principle involves a relay independent of system conditions and dependent on direction of current flow for its operation, and on

distance from the fault for its time. Many improvements and developments have been made as the result of operating experience, which also has resulted in a better understanding of its operation on the part of operating engineers, many of whom now use the impedance relay as their standard type of protection.

Discussion

H. P. Sleeper: I am interested in the *C Z* relay as being a development which I think has quite a few economic possibilities; in fact, I think the choice of the *C Z* relay for any particular system of protection is governed by the economics which it may effect.

The relay has for its principal application, in my opinion, its use on complicated systems. Unfortunately, transmission engineers of today seem to delight in complicating rather than simplifying high-tension distribution systems. Obviously, their desire is to carry the load, and they give it to you as it is and say, "Here it is, now protect it," and sometimes it is easy and sometimes it is not so easy.

Time-element directional protection has heretofore been used almost universally for networks. However, a complicated network does give rise to problems which are difficult to solve, if one desires perfect operation, namely, to open only the circuit breakers on the unit in trouble.

There are two solutions to such a problem. One is to use balanced protection between pairs of lines. This is frequently uneconomical, because it sometimes means installing lines that are not actually needed and cannot be justified on a basis of economical transmission. The other solution is to use some form of relay protection which takes care of the line by reason of faults on that line, and is not dependent on time elements in other sections of the system. The *C Z* relay does this better than any other relay that I know of that is now on the market, so for that reason I think the system economics to be afforded by the use of the *C Z* relay are very pronounced.

Now, the other problem which has been discussed by the author, namely, obtaining the correct potential for the *C Z* relay, is one that gave considerable trouble at first. It has been very ingeniously solved, and I am told by operating men who are using these relays with the low-voltage potential that they operate very successfully. We do not have any such installations on our own system.

There are, in my opinion, some very definite limitations to the application of this relay which should be carefully watched by operating engineers. For instance, the relay has sometimes been advocated for balanced protection of parallel lines. It is my opinion that the *C Z* relay here does not afford the protection possibilities that straight balanced protection affords. It is well recognized by all operating people that the time of disconnection of faults from a system should be made as short as possible. This is necessary first to relieve the bump from the system and hold synchronous apparatus in operation, and, second, to increase the inherent stability of the system, which is, of course, a most important point.

In this application, with the parallel lines available, I much prefer to use straight balanced protection. This is fundamentally due to the fact that a balanced relay can be set for a definite time. For instance, if we consider any type of balanced protection, on each end of two parallel lines, these relays may be set as fast as 0.2 or 0.1 sec. If we use 0.3 sec. as a fair time for breaker opening, the first end at least will be disconnected in, we will say, 0.2 for the relay plus 0.3 for the breaker, or 0.5 sec. total. If there was a source of feed on the other end, that end would have been disconnected simultaneously, so that in 0.5 sec. the fault would be removed from the system, which is about as fast as it can be done.

The CZ relay, on the same application, would have taken more nearly 0.5 sec. for relay operation, because the fastest time that a CZ relay can operate, in the vicinity of 300 per cent current or under, is about 0.5 sec. Add 0.3 for the breaker, and that gives 0.8 for the clearing of the fault on the one end. The other end may have cleared simultaneously, but probably would have taken more nearly 0.75 sec., which is usually assigned for its operation, so, adding 0.3 for the breaker, we get 1.05 sec., which added to the 0.8 on the other end is 1.85 sec. for the disconnection of the fault. This may be reduced possibly to the 0.8 operation on both ends simultaneously, if power is available on both ends. However, on the average location of fault and on the various connections of a system, namely, with feed-back and without feed-back on the two ends of the lines, the time will run about 30 per cent higher for a CZ relay to disconnect faulty parallel lines. Therefore, I prefer to use straight balanced protection. However, the CZ relay does afford an excellent application in connection with balanced protection, namely, as a back-up relay for the balanced relays. That is, after one line has been disconnected, the CZ relay can be used as a back-up for the single line that is left, and will give selective operation for that line in connection with the remainder of the system. I find this to be a most satisfactory application of these relays to balanced lines.

The matter of the potential source and using the compensators for getting the correct potential is one which must be resorted to, if high-tension potential cannot be used. I prefer not to use it, if I can avoid it, because it employs additional material that must be checked out and maintained, etc. Those who have done relay work in the field will agree with me, I think, that relay men are much like soldiers and, as "battles are won by tired men," relay connections are usually checked by tired men, on account of the hours they have to work, and so I prefer to avoid any possible complications.

A most happy solution, I believe, is the one suggested in the paper, whereby bushing potentials are used to supply the source for the restraining element of the relay and other potentials, low-tension or whatnot for the directional elements. I believe this will prove very satisfactory and good economies.

Our own system has approximately 30 such installations of standard type CZ relays. We had some of the original relays and ran into trouble with them because at that time they were not entirely satisfactory mechanically. However, since those have been ironed out during the past year, we have had perfect operation on our CZ relays.

The factor of safety on the setting of CZ relays is very large indeed, both over the ranges of connected capacity and over the ranges of incorrect calculation or errors in calculation. We are setting our relays with a rather high factor of safety and, as I stated, we have had no incorrect operations due to incorrect selection.

I think the CZ relay has a very definite field; I think it has come to stay; I think it has very definite applications and also very definite limitations. I foresee for it a future which can be compared with that of other relays which today are known as standard types.

In conclusion, I should like to ask the author two questions: First, is there anything that can be done to speed up the zero-voltage operation of the relay, which I feel should be faster than it is now? Second, is any trouble to be anticipated by the additional time element which is introduced by the interlocking of the directional element with the operating element?

O. C. Traver: When the original CZ paper was presented by Mr. Crichton about five years ago in Pittsburgh, I expressed the opinion that the general principle was sound. I still believe this, although I have some reservations when it comes to wide-application.

The impedance principle is beautifully simple from a single-phase standpoint and we become, perhaps, a bit over-enthusiastic as to our expectations of what can be done with the relay system.

The author has not evaded this issue, but has brought to our attention the number of relay elements which may be required. If I understand the paper correctly, in order to secure complete and proper protection with the impedance scheme, sixteen elements are specified for one end of one three-phase line. This may be justified in certain instances, but I cannot think that the recommendation is intended to be general.

In a paper presented recently at Chicago by Messrs. Crichton and Graves, the power type of ground relay was recommended in preference to the three extra CZ relays. In view of the experience, for instance, as told by Roy Wilkins last September at the Del Monte Convention (where he reported that out of 1500 operations there has been no indication of faulty operation), the record seems excellent for the simple residual-power relay. If such a record can be maintained, certainly the simplicity of the one time-power relay commends itself in preference to the use of the three extra impedance relays.

A complicated network as mentioned in the paper, becomes more difficult to protect with definite time. But if inverse-time relays are used on a system having many feeds, more circuits can be relayed with a less maximum delay. The inverse-time relay requires greater thought than the definite time relay in its application, but it seems clear that the impedance relay requires even more in spite of Mr. Sleeper's suggestion that you could not set it wrong. I think in looking over the instruction book, for instance, which gives a page or two of information as to how to set it, and many tables in order to arrive at the right setting, there must be something to the problem.

The use of a small number of impedance relays on certain parts of a system otherwise protected by straight overcurrent relays will require very careful analysis before application. The impedance relay works correctly, as has been said, at the generating end, but I feel certain that for many resistance faults, the time may be higher than if straight overcurrent relays are used throughout. In fact, if impedance relays are applied at the power-station end, time probably can be saved by using the overcurrent relay also in addition, taking the time of whichever one is the more rapid.

The curves shown in the paper are not, to my mind, independent in time with respect to the current flowing; in fact, they have a tendency to rise with the increasing current above a certain value. That tendency to rise, it seems to me, is incorrect. It is obviously wrong, if you have current twenty times the setting of the relay to allow it to take half a second or a second longer time to operate than if you had three or four times normal. It means that one must set the relays higher on the average over the entire system on that account; therefore, if brought down to definite time action, the operation would be more prompt.

The question of "locking" relays has been brought up by Mr. Sleeper. Although we have with good results, long made use of the idea of requiring operation of the directional relay first before permitting the overcurrent relay to start, it is not the ideal, because of the variable time that the directional relay adds to the over-all operation of the combination. If a three-phase fault happens to be very close, by chance, and the voltage therefore low, and if the directional relay accordingly takes a fraction of a second, say a quarter of a second as a distinct possibility, that quarter of a second must be added to the total time. We are, therefore, adding a variable which is going to increase the over-all and although it may be the better of the two evils, still, it is something that needs elimination.

The new type of directional element referred to in the paper mentions only one feature, and that is the method of connection to the line. We have used this 90 deg. connection at Schenectady for over ten years, and we like it. We feel sure that the CZ will profit by that same connection. The alternative 30-deg. connection has also been used to advantage in a few instances.

W. W. Edson: (communicated after adjournment) On incoming lines with large leading power factors or on outgoing

lines directional elements will normally be closed. In case of a fault ahead of the station will the directional contacts drift open before the current contacts close? In other words, has this new directional control circuit helped this condition?

At the bottom of the third page it is stated that the use of a resistor in the potential circuit of the directional elements will be discussed in a later section, but I do not see this subsequent reference. This is probably applicable to the use of condenser bushings.

Special caution should be given for the use of low-tension potential transformers where there are high- or low-tension transformer circuit breakers which might separate the potential transformers from the lines they are protecting. Also the equipment becomes quite complicated if there are two or more transformers operating in parallel as the per cent inductive drop to be compensated for varies with the number of units in service.

For sandy or rocky localities having high ground resistance, the KX compensators in Fig. 10 may not be applicable as the voltage vectors might take positions similar to those for an ungrounded neutral system.

H. A. McLaughlin: In closing, we agree with Mr. Sleeper very heartily, that the impedance relay has limitations, and we feel that, in applying it, great care should be used in recognizing these limitations. We also agree with them that the balanced protection, from a purely theoretical point of view, is by far better than anything else, because of the very short times that are involved.

As pointed out by him, the difficulty with the balanced protection is for the single-line operations, and in that case the impedance relay offers a very nice solution for a back-up protection. If it would be possible economically to justify putting lines in pairs, and only operating them in pairs, the balanced protection would certainly be the one to use.

I want to answer the two questions of Mr. Sleeper in regard to the zero time. That zero time is now at the minimum that we have been able to get, and that is 0.25 sec. for this zero voltage, and 200 per cent current. Now, as current goes up with zero voltage, that time will be reduced considerably.

In regard to the time delay introduced by the directional element, I did not point out that the voltage used on the directional element and the voltage used on the impedance element are not the same ones, so that, for a line-to-line fault, the voltage on the impedance element will never be reduced to less than line-to-ground value and, likewise, for a ground fault, the voltage on the directional element is a different one from the one on the restraining element, and there again, it would never be reduced to less than line-to-ground voltage.

Under those conditions, we have found that the additional time involved is something of the nature of two to three cycles, and is constant over the range of operation. In other words, the voltage is sufficiently high that variations in current do not make any appreciable variation, it is simply a constant addition of between two and three cycles.

In regard to Mr. Traver's remarks, the number of elements is perhaps higher than if straight overload relays are used. However, the only reason for using impedance relays is that you cannot always get the result you want with the other relay, and for that reason you have to justify some further complications in the system. If you could not justify them, if you could get the results you wanted with the simple system, the simple system would be the one to use.

In regard to inverse-time relays, there you introduce a variable that will have a very definite effect on the time of operation of the relays, whereas with the impedance relay the fault may vary over a considerable range without greatly affecting the time of operation of the various relays.

That brings up another point that Mr. Traver mentioned, that is the fact that, from the curves, he did not think that the time was constant and independent of current. If you look at these curves and take, for instance, 300 percent current and 6 $\frac{1}{4}$ volts, you will find that is approximately 0.75 sec.; then going on and taking 600 per cent current, that is double the current and double the voltage, you will find that the time is very nearly the same, it might be a fraction of a second higher, and so on, out to practically 1000 per cent of the relay setting, the time rises a very small amount, not enough to affect the selectivity of the system to any great extent, and on very few systems, I think, is there more than a variation of 5 to 1 in the ratio of minimum and maximum short circuit, at any one point.

The matter of setting relays was mentioned by Mr. Traver. Subsequent to the publication of the instruction book that he saw, with the large number of tables, a different method of setting has been developed whereby any setting may be arrived at by the use of a simple formula and the setting obtained directly. Since that, a chart has been developed by means of which with a straight edge the setting may be arrived at without any calculations at all. The various tables are not used at the present time.

In regard to using the impedance relays in systems where other relays are already used, at the generating-station end is the only place where they will give any definite gain in result. Putting them at the generating-station end is exactly equivalent to cutting one step out of the loop. In other words, you reduce the total time by one step, and if the system then becomes large enough so that it is desirable to cut out another step it may be accomplished by putting them at the stations nearest the generating station.

In the first case mentioned by Mr. Edson where a change of direction of power flow takes place with the occurrence of a fault, the question is not merely of the directional contacts drifting open. In each case there will be a definite force tending to open or close the contacts depending on whether the fault current is flowing towards the station or away from it.

The use of the resistor in the directional element may have an advantage when potential is taken from condenser bushings since it somewhat reduces the burden.

In using low-tension potential and compensators it is only necessary to compensate for the drop of one transformer bank. As Mr. Edson points out, caution should be exercised in seeing that the switching is so arranged that one bank with compensators is always in service.

In the event of a high-resistance fault the KY compensators when arranged as shown in Fig. 10 will still supply a voltage proportional to that existing in the high-tension side. The drop, however, may be so small that the relay will operate very slowly due to the high restraining voltage. In cases of this sort the current will also be considerably reduced and may not be sufficiently high to operate the relay. In this case its effect on the system will be small. Where this condition exists the system described in the first paragraph under Special Applications is recommended.

Automatic Switching of Incoming Lines and Transformers Supplying Power to A-C. Substations

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Synopsis.—The early applications of automatic switching were confined principally to equipment which supplied or handled the outgoing power, such as conversion apparatus and outgoing feeders. As the field broadened and the capacity of the stations increased, it became necessary to provide for greater continuity of incoming power. In order to meet this requirement it has been customary to bring in two, and occasionally three, incoming lines.

It is the purpose of this paper to describe briefly some of the more common forms of this type of automatic switching. By making a few minor modifications of the schemes which are described it has been possible to control automatically a complete loop or ring system.

Balanced power or parallel incoming lines are quite common.

Ordinarily two such lines are used, although as many as six have been contemplated. All lines are usually carrying power to the substation unless a fault has developed. When cleared of the fault, the line (or lines) is automatically replaced in service.

In the case of the preferred-emergency type of equipment, it is customary for one line (the preferred) to carry the substation load. The second line (emergency or standby) takes this load upon failure of the first line. The application of these units to a system usually determines the sequence of operation between the two lines. A few typical combinations are described and illustrated.

A brief description of automatic synchronizing and transformer switching has been included.

INTRODUCTION

THE early application of automatic switching was confined principally to rotating machinery such as rotary converters and motor-generator sets. In the development and extension of automatic control, it was a logical step that attention should be given to the switching of a-c. incoming lines which supplied power to substations having a number of distribution feeders. These feeders were usually at 2300 volts and of the automatic reclosing type. The essential purpose of the incoming line equipment was to have two (or more) sources of power available, using one as the normal or preferred and the other as the emergency or standby.

A parallel development has been one which resulted in equipments suitable for controlling parts, if not all, of transmission systems, and load responsive switching of transformer banks. It can be seen that the field of application of this kind of equipment is very broad. This paper will be confined to the more common types.

At present a total load of over 500,000 kv-a. is being taken care of by these equipments. The voltages range from 2.3 to 132 kv., while the capacity per substation, so controlled, averages approximately 5000 kv-a., the lower limit being 1000 kv-a. and the upper is slightly in excess of 25,000 kv-a. It is felt that the application of these equipments will be greatly increased in the future. There are many substations at present that are being fed by one incoming line. Extension of the system in the future, and perhaps, in addition, the increasing importance of the load supplied by such stations may result in connecting these stations to another nearby line or lines. Again, a new or existing station may be called upon to supply a type of load where continuity of service is a primary consideration.

The customary solution is to bring in another source

of power through a second and sometimes a third incoming line. The use of two incoming lines for such installations is quite common. Another example of this type of equipment is in the automatic control of loop or ring systems, which, at times, require automatic synchronizing in addition to the usual control. Automatic supervisory equipment is sometimes used in conjunction with this form of control.

It is not the purpose of this paper to cover the various system protective features, since this is a subject in itself. Attention will be given to the operations performed by the automatic control from the point of the individual installation rather than the system in general. However, it might be well to point out in passing that the method used in applying protective devices to a system made up in part or in whole of automatic stations is not always the same as in the case of manual stations, even though the final result may be the same. With manual operation the next move is sometimes up to the operator. In the case of automatic operation after the protective or other relays have functioned, the remaining relays must be ready at once (if necessary) for further operation, or those which have just operated must reset automatically and be in readiness for a resumption of their former operation. This last feature requires not only a study of the resetting features of the various protective devices, but a study of the system as a whole, before and after a particular switching operation. Consequently, it may be found that different relays are used for automatic operation, although basically there may be no outstanding difference between such relays and those used for manual operation. The question of maintenance is another important factor. This feature requires greater reliability of relays used in automatic stations.

In addition to the different types of incoming lines there has been prepared a brief description of automatic synchronizing and transformer equipments. The application of these various forms of automatic switching

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is given under the various headings. Six common types of automatic switching are illustrated by one-line diagrams. These substations are assumed as feeding power to outgoing distribution feeders of the automatic reclosing type. Service conditions and many other local factors usually decide what type of equipment should be used.

BALANCED POWER OR PARALLEL INCOMING LINES

A very common form of incoming lines are the parallel or balanced power as illustrated in Fig. 1.

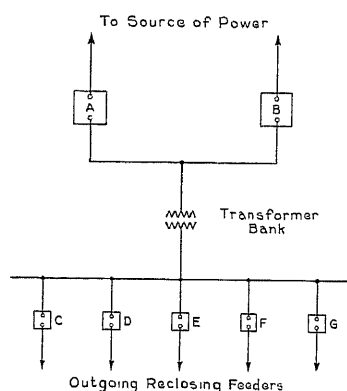


FIG. 1—ONE LINE DIAGRAM. TWO-BALANCED POWER OR PARALLEL INCOMING LINES

Normally, both A and B are closed. A or B trip on unbalanced power and reclose on voltage restoration.

This substation is fed from the same generating station by means of two lines of practically equal impedance. In case of a current unbalance as caused by a fault on one line, the oil circuit breaker feeding this line from the generating station is tripped, as well as the corresponding breaker at the substation.

The substation breakers reclose only when three-phase voltage has been established on the incoming line for a definite time. This means that the corresponding generating station breaker must be reclosed either manually or automatically and attempt to reestablish service on the line. In case of short circuit conditions, only a few such attempts are made and consequently the substation breaker does not reclose. In this manner the brunt of the overload duty is thrown on the generating station breaker. Operating experience has shown that one breaker operating on the ordinary reclosing cycle will reestablish service or lock-out and that there is little to be gained in putting a second breaker through this cycle under conditions which caused the first breaker to lock-out.

The three-phase voltage indication for a definite time shows that the fault has been removed and the line clear. The time delay is used in order to permit any protective relays to operate before the substation breaker is closed. At times it also permits certain loads to be applied gradually in a step-by-step sequence. At the expiration of this timing action the substation

incoming line breaker closes and normal connections are restored.

Occasionally it is desired to use single-phase voltage on the incoming line as the indication for closing. Cases may be found where one line wire has grounded in such a way that no fault current would be obtained when the generating station breaker closed, yet due to the fact that the voltage indication was taken between the two good line wires, the incoming line breaker at the substation would reclose. Upon reclosing, a fault current would be obtained. This may be readily seen if it is assumed that the wire breaks at an insulator in such a way that the grounded end is away from the substation, and normal three-phase voltage is maintained on the substation bus by means of the other incoming line.

Therefore, due to the fact that single-phase voltage indication may result in improper reclosing action on the part of the substation breaker, it has been found advisable, when single-phase voltage indication is used, to add a relay which will permit the breaker to reclose a certain number of times in a predetermined time.

PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS SOURCES

This type of equipment may be considered as a modification of that just described. Due to the fact

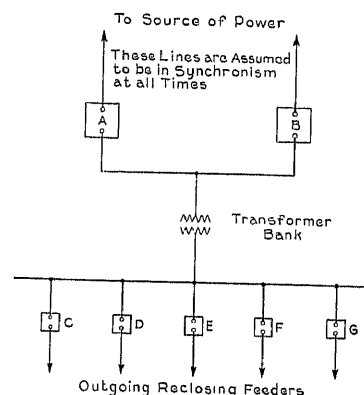


FIG. 2—ONE LINE DIAGRAM. TWO PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS SOURCES

Normally, either A or B is closed, and trips on voltage failure, provided voltage conditions are proper on the other (emergency) line. Restoration of voltage to the preferred line results in retransfer of the load to that line. Under certain conditions A and B may be closed simultaneously for a short interval. Either line may be made the preferred

that the two incoming lines, Fig. 2, are of different impedance, enough current unbalance might be obtained (to operate any protective relay) if both breakers A and B were closed for any appreciable time. In addition, any connected load on these lines may require that both lines be normally disconnected from each other. Consequently, the load at this substation is normally supplied from one line called the preferred or normal. The other line, called the emergency or stand-by, is used only in case it is in good condition and voltage

has failed on the preferred line. The choice as to which line is the preferred or emergency depends on local conditions, and can readily be made by a transfer switch.

Undervoltage releases on the oil circuit breakers are not recommended for this service. Their principal

and some time will be required before reconnection may be made. If time delay action is provided on the undervoltage releases, it is then found that there is a number of operating conditions that require the addition of suitable contacts. It has been found that such contacts can be placed more satisfactorily on a panel-mounted device than on an undervoltage release. These panel-mounted devices together with potential trip coils, energized from the "opposite" line, give the desired operation.

Fig. 3 illustrates the necessary panel-mounted devices for the control of such equipment. This panel may be used for controlling a-c. or d-c. operated oil circuit breaker mechanisms. On the top section are mounted four undervoltage relays. Two relays are used for each line, one for each of the two phases. Fig. 4 gives the elementary diagram of control for two preferred-emergency lines from synchronous sources.

The general sequence of operation of such an equipment is as follows:—Assume that the preferred breaker is closed, then upon occurrence of undervoltage on any phase or phases of the preferred line, its undervoltage relays start to drop out and after a time delay will close a set of contacts. Operation from this point on depends on the condition of the emergency line. In other words its voltage conditions must be satisfactory, otherwise there is little to be gained in making a transfer. In order to make a transfer all three phases of the emergency line must be in good operating condition as determined by its respective voltage relays.

Assume conditions are thus far satisfactory for a transfer. A timing relay with a relatively longer setting is placed in action. This type of relay, as shown at the extreme left and right at the top of the middle section, Fig. 3, is energized from the emergency line, but is controlled by the undervoltage relays on the preferred line. The timing relay is used to prevent a transfer due to momentary voltage "dips" and also to allow any

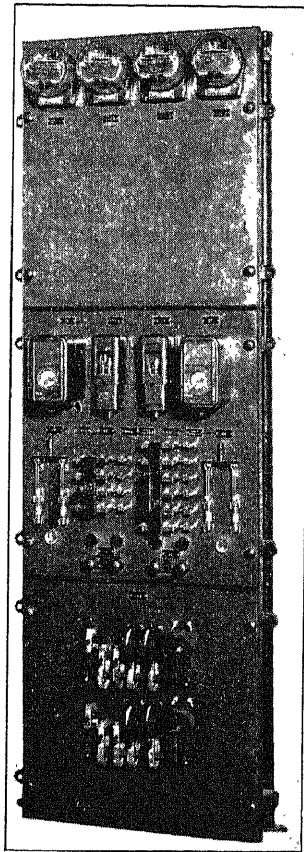


FIG. 3—PANEL-MOUNTED DEVICES FOR CONTROLLING PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS OR NON-SYNCHRONOUS SOURCES, AS WELL AS FOR CONTROLLING NON-PREFERRED INCOMING LINES

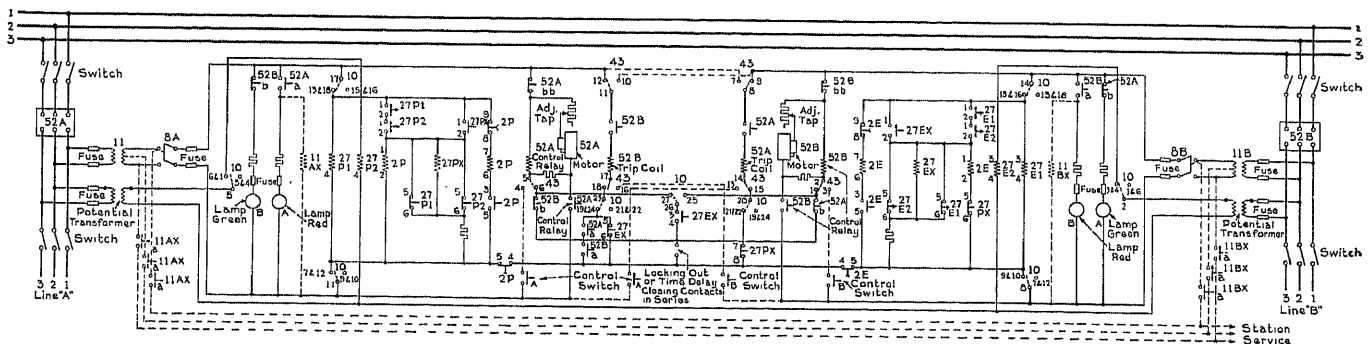


FIG. 4—ELEMENTARY DIAGRAM FOR TWO PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS SOURCES

disadvantage lies in the fact that if they are instantaneous in action, they are apt to drop out on short-voltage "dips." Again, both sources may become deenergized which results in tripping a breaker when nothing is usually gained by such an operation. A subsequent return of voltage finds both breakers open

protective scheme (especially at the source) to operate and clear a fault which may cause such "dips" on the supply source.

At this point it might be well to state that as the result of a number of tests it has been found that the ordinary oil circuit breaker mechanism does not operate

fast enough to make a successful transfer which will result in holding in all of the so-called "instantaneous" undervoltage releases commonly used with induction motor starters. At times 50 per cent of such releases have been held in, where the oil circuit breaker mechanism has been purposely speeded up. Moreover, if a group drive is used, it seems better to slow up the transfer (and bridge the usual momentary voltage "dips") and drop off all of the induction motors. This also results in less strain and longer life to the transfer equipment.

If undervoltage conditions still exist, usually from 5 to 10 sec. or over, then the preferred breaker is tripped. This tripping action is obtained by voltage from the emergency line. As soon as the preferred breaker opens the emergency breaker is closed. The control is so interlocked that when a transfer is made in this direction the preferred breaker must be open before the emergency breaker can close. The reasons for this are that a fault may exist on the preferred line and if both breakers were closed simultaneously this fault would be reflected to the emergency line, which would probably trip the breaker at the supply source and result in a loss of voltage and no means of opening the preferred breaker. Over-current protection on these equipments is usually dispensed with and potential tripping only is used in connection with the transfer operation.

Consequently in making the above transfer the load is momentarily dropped. However, if voltage remains on the emergency line and also returns to the preferred line for a definite length of time, then the preferred breaker is closed after which the emergency breaker is immediately opened. This temporary overlap is so short that protective relays will not operate, and results in a retransfer without dropping the load.

There is a number of other conditions that such an equipment has to meet. These requirements to a certain extent account for the presence of the two relays in Fig. 3, located between the two timing relays on the middle section. Such conditions are briefly: the positions of the oil circuit breakers, the voltage conditions on their respective lines, the order in which voltage returns to the deenergized lines, type of oil circuit breaker mechanisms, etc. Such an equipment would probably appear to have only a few possible operating combinations from which the relays have to work and establish the proper sequence. Upon further investigation it is found that there is a number of such combinations, all of which are practical conditions and which can be taken care of by proper connections or choice of devices.

This type of equipment is usually furnished with two transfer switches. One is used to select the "preferred" and "emergency" sources from the two incoming lines. The other is used to enable the equipment to be operated entirely automatically or entirely manually. These two latter functions are kept independent of each other.

As mentioned above, either a-c. or d-c. operated oil circuit breaker mechanisms may be used with standard oil circuit breakers. A small number of auxiliary switches is included for interlocking purposes.

The equipment controlled by the devices as shown in Fig. 3 was used to supply power to an automatic railway substation. The two contactors on the bottom section supplied control power to the machine devices and have no direct function with the preferred-emergency unit.

PREFERRED-EMERGENCY INCOMING LINES FROM NON-SYNCHRONOUS SOURCES

An application of incoming lines of this type is shown in Fig. 5. It will be noted that the two incoming lines are assumed to be out of synchronism at all times. Therefore, breaker *A* must be open before *B* can close, and vice versa. If this is not done, then the incoming line equipment will connect two generating stations which may be out of synchronism. Either line may be made the preferred as explained above.

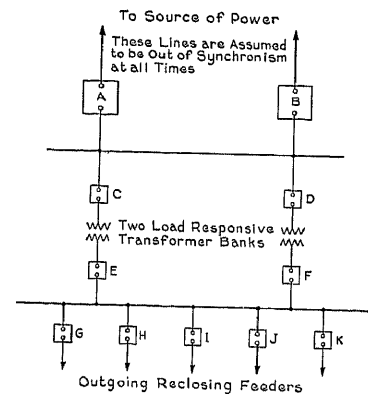


FIG. 5—ONE LINE DIAGRAM. TWO PREFERRED-EMERGENCY INCOMING LINES FROM NON-SYNCHRONOUS SOURCES

Normally, either *A* or *B* is closed, and trips on voltage failure, provided voltage conditions are proper on the other (emergency) line. Restoration of voltage to the preferred line results in a retransfer of the load to that line. Breakers *A* and *B* are not closed at the same time. Either line may be made the preferred.

Undervoltage conditions for a predetermined time will cause the preferred breaker to be tripped by voltage from the emergency line after which the emergency breaker is closed. A return of voltage to the preferred line, will, after a time delay, cause the emergency breaker to be tripped and the preferred breaker to be closed. No attempt is made to go from one line to the other unless the line to which the transfer is to be made is in better or as good condition as the one that has been supplying power previously.

If both breakers are open and voltage returns to one line, the breaker on that line will close. If both breakers are open and voltage returns simultaneously to both lines, the preferred breaker will be closed.

Although it is assumed that the supply sources are usually out of synchronism, there may be cases where a tie-in between these sources may result in the two lines

being in synchronism. Consequently, at such times a retransfer can be made from the emergency to the preferred line without dropping the load. Such switching can be made when proper voltage conditions exist on both lines. In order to make certain that these voltages are of the proper phase relation it is necessary to add a synchronism check relay to the customary devices. If the conditions are such that this relay does not operate then the emergency breaker must open before the preferred breaker can close. If the conditions are satisfactory, then the preferred breaker is closed, after which the emergency breaker is tripped.

With the above exceptions of sequence and application, the preferred-emergency type of incoming lines from non-synchronous sources, operate similar to those from synchronous sources.

Two load responsive transformer banks are also shown in Fig. 5. One bank carries the substation load during light load periods. The second bank is connected when the load on any one phase increases to a predetermined value. When the load on all three phases decreases to another predetermined value the second bank is disconnected.

The indication for bringing on or taking off the second bank is obtained from current transformers connected in the line. Where two or three power transformers are used it is found advisable to parallel the current transformer secondary circuits and totalize the current on each phase. This permits the use of a fewer number of master relays with a resulting simplification of relay

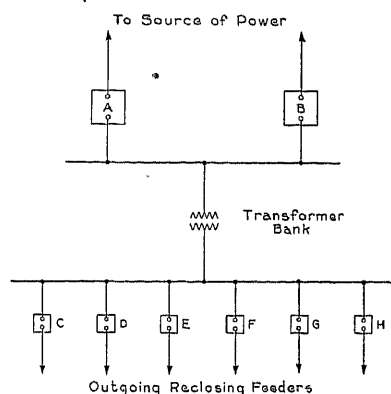


FIG. 6—ONE LINE DIAGRAM. TWO NON-PREFERENTIAL INCOMING LINES

Normally, either A or B is closed and continues to remain in this position until its voltage fails and proper voltage conditions are present on the other line. No preference is given to either line under a majority of conditions

calibrations. If one set of relays is used for each bank it becomes necessary to provide a gap in the relay calibrations, in order to avoid having two sets of relays calling for opposite switching action.

Differential and thermal protection are ordinarily provided. Upon failure of one bank it is immediately disconnected and locked out, the remaining bank then takes its place and no further load responsive switching

is performed until the lock-out relay or relays are manually reset. This enables the equipment to be inspected and the cause of failure ascertained before the unit is replaced in service. Either bank may be made the "leading" or "trailing" by means of a transfer switch.

NON-PREFERENTIAL INCOMING LINES

At times it has been found advisable to allow either incoming line to feed the load as long as proper voltage

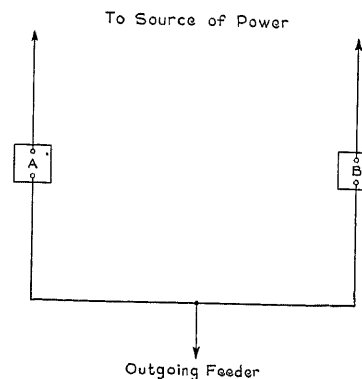


FIG. 7—ONE LINE DIAGRAM. TWO PREFERRED-EMERGENCY INCOMING LINES COMBINED WITH OUTGOING RECLOSING FEEDER

Normally, either A or B is closed and trips on voltage failure provided voltage conditions are proper on the other (emergency) line. Restoration of voltage to the preferred line results in a retransfer of the load to that line. A and B may be closed simultaneously for a short interval, depending on whether or not the two incoming lines are in synchronism. A limited number of reclosures is available in case of overload conditions

conditions exist on its line regardless of conditions on the other line. If voltage fails on this line and conditions are satisfactory on the other, then its breaker will trip and the other close. The other line continues to feed power to the load regardless of a return of voltage to the first line. Due to the fact that a breaker can remain closed as long as voltage remains on its line and no preference is given under a majority of conditions, such forms of incoming lines are called "non-preferential." No transfer switch is necessary in order to establish preference. A certain amount of preference is obtained by the relays in order to take care of cases where both breakers are open and voltage returns to both lines practically simultaneously. In order to secure positive closing action in such a case, one breaker must be given preference over the other. Fig. 6 gives a one line diagram of this type of equipment.

Due to the fact that one breaker is always open before the other can close, these equipments may be connected to synchronous or non-synchronous sources.

COMBINED RECLOSING AND PREFERRED-EMERGENCY INCOMING LINES

Another common application is one in which two preferred-emergency incoming lines supply only one outgoing feeder. Overload protection is provided so as to trip whichever breaker is closed. If overload

conditions persist, a certain total number of reclosures is permitted, after which the equipment is locked out. Fig. 7 illustrates the connections of such an equipment into a system. Fig. 8 illustrates an outdoor unit for such service. Such a unit is a combination of two incoming lines and one outgoing reclosing feeder.

Undervoltage conditions are taken care of in practi-

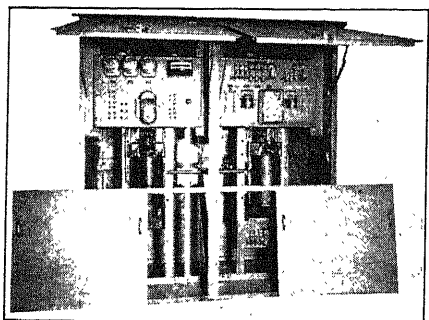


FIG. 8—COMBINED OUTDOOR A-C. RECLOSING FEEDER AND INCOMING LINES FOR 4000-VOLT CIRCUIT

cally the same manner as the above preferred-emergency units. The combined equipment can be used for synchronous or non-synchronous sources and can also be made non-preferential.

PARTIAL AUTOMATIC PREFERRED-EMERGENCY INCOMING LINES

A limited form of incoming line equipment is obtained by using one manually operated and one motor-operated breaker. The manually operated breaker is connected to the preferred line while the motor-operated breaker is connected to the emergency line.

Upon failure of voltage on the preferred line, its breaker is tripped after which the emergency breaker is closed. The equipment remains in this position until the retransfer is made manually.

A disadvantage of this type is that the emergency line may subsequently fail with its breaker closed and voltage return to the preferred source. Since the preferred breaker is manually operated it is necessary to wait for the arrival of the operator or inspector to effect the retransfer.

AUTOMATIC SUBSTATIONS SUPPLIED BY MORE THAN TWO INCOMING LINES

Fig. 9 shows a one line diagram of an automatic station that is supplied by a number of incoming lines with their respective transformer banks. Line A and its associated transformer are the emergency and take the place of any line or transformers that have failed. Lines B, C, and D are the normal sources of power.

Normally line D and its associated transformer feed the low-tension bus sections which are now tied together. Whenever sufficient load demand occurs the second bank is brought on and the first bank carries only its section of the bus with its connected outgoing

feeders. Continued load demand brings on the third bank with the same resulting connections. The low-tension bus is now completely sectionalized and each incoming line feeds its share of the outgoing feeders direct from the generating source. This results in radial or stub feed direct from the source to the load and also in a simple relay protective scheme.

If any line or bank fails, it is taken out of service and replaced by the emergency line. The remaining lines (in good condition) feed their share of the load direct as in the case of switching under normal conditions. The relays make the proper set up, after which the panel-mounted drum controller completes the required switching operation. The use of a drum controller for such equipment greatly decreases the number of contacts necessary on the relays and also results in a positive sequence of operation.

A total capacity of 27,000 kv-a. is handled by the automatic switching equipment in this station. The outgoing reclosing feeders in this particular installation are 2540/4400 volts using single-pole breakers with independent mechanisms and reclosing relays.

AUTOMATIC TRANSFORMER LOAD RATIO CONTROL EQUIPMENT

Automatic switching equipment has been recently applied to transformer tap changing (under load).

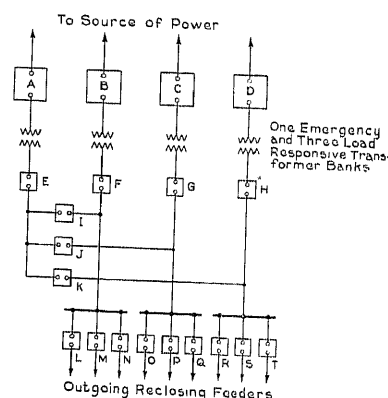


FIG. 9—ONE LINE DIAGRAM. THREE INCOMING LINES WITH LOAD RESPONSIVE TRANSFORMER BANKS TOGETHER WITH EMERGENCY INCOMING LINE AND TRANSFORMER BANK

Normally, D and H; I, J, and K are closed. As substation load is increased C and G, and B and F, are closed (successively) as required. Low tension bus is sectionalized (by opening I, J, or K) whenever two or more banks are operating, giving radial feed from generating station to load. As the load decreases the reverse operation takes place. On occurrence of line or transformer failures all lines and respective transformers in good condition feed their corresponding low tension bus sections, giving the above mentioned radial feed. The emergency line and bank (Breakers A and E) replace any defective line and bank

When two banks are used, either bank may be operated automatically or manually and when automatic may operate from individual or common master elements.

To adjust the line voltage in accordance with the changing load, the high-voltage windings have eleven taps of $2\frac{1}{2}$ per cent each. To permit a change of taps without interrupting the load, a part of the

high-tension winding is made in two sections, normally operating in parallel and dividing the load equally. Each of these winding halves is connected to an eleven-point ratio adjuster (Fig. 10), and the resulting circuits brought out of the transformer tank to two three-pole oil circuit breakers.

Consequently, it is possible during the tap-changing period to open circuit one section in each phase, and change the voltage tap in this open-circuited section while the other section temporarily carries the entire load of the transformer. Copper of ample cross-section and the very short transition period permits this to be done. The same change is then made in the second half. The entire change from one voltage to the next requires only 8 sec. For brief periods (less than $1\frac{1}{2}$ sec.), when both breakers are closed but the two

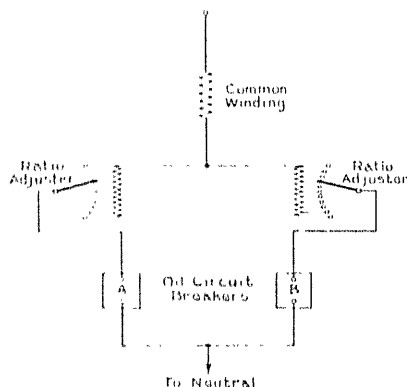


FIG. 10 ONE LINE DIAGRAM. LOAD RATIO CONTROL

Normally, *A* and *B* are closed. When voltage correction is required, as determined by suitable master element, breaker *A* is opened and corresponding ratio adjuster moves one point. Breaker *A* then closes and breaker *B* opens, followed by its corresponding ratio adjuster moving one point and in the same direction as movement of other ratio adjuster. Breaker *B* then closes. This sequence is continued as long as necessity for voltage correction is indicated.

ratio adjusters are one tap apart, an internal circulating current exists, which, however, is kept within predetermined limits by sufficient inherent reactance in the transformer windings.

A motor-operated mechanism mounted on the transformer truck insures a properly timed operation of the internal ratio adjusters and the external circuit breakers. It is essential that the three corresponding ratio adjusters of the three phases move simultaneously from one tap to the next; therefore, these ratio adjusters are mounted together on the same shaft with full-phase insulation between them. Turning the driving shaft of this gear train one complete revolution will first change one set of three adjusters one step, then lock this set, and then turn the second set one step. Provisions are included also, so as to make certain that both sets change their taps the same amount in a predetermined time.

Contact-making voltmeters do away with any manual starting of the mechanism. If the line voltage deviates from a set value for a predetermined time, the tap-

changing mechanism is automatically put in motion in one direction or the other to bring the voltage back to normal.

Two contact-making voltmeters are used on each of the two transformers, one adjusted to respond to a narrow range of voltage variations, while the other one is set for much wider differences in voltage. If the line voltage rises or drops only slightly, and if this condition persists for a predetermined length of time, the transformer will shift to the next proper tap. If, on the other hand, a considerable rise or drop occurs, the second contact-making voltmeter will respond, and will cause immediate adjustment without any time delay.

AUTOMATIC SYNCHRONIZING OF INCOMING LINES

In general, there are two conditions under which an incoming line should be synchronized with the bus. One condition is where two sections of a system are already tied together at some other point. This means that the two voltages, at the open breaker terminals, are stationary with respect to each other, but may have a certain phase displacement due to circuit conditions.

In case two sections of a system are cut apart it will be found that the two voltages at the open breaker terminals will be rotating with respect to each other at a frequency equal to the frequency difference between the two generating sources. The equipment in the automatic substation has no control over the governors in either generating station, so that the closing operation of the breaker is determined by other factors which are: first, the frequency differential must be less than a certain value and secondly, the breaker closing impulse must be given enough ahead of synchronism so as to enable the breaker to be closed when the point of synchronism is reached, in other words, at "12 o'clock."

The calibration of the synchronizing relays for the two different operating conditions is such that one is inoperative under conditions under which the other functions.

It has been found advisable to use a separate synchronizing relay combination for each breaker. Different breakers have different closing characteristics, and even though a number of breakers could use a common synchronizing relay it has been found that the resulting scheme would be more complicated, less flexible, and more expensive than the individual control.

Discussion

E. L. Hough: At the present time, there are few things that cannot be done with automatic switching equipment, and it is usually a question of proper economies in applying automatic control.

In checking over Mr. Anderson's figure of 500,000-kv-a. capacity being taken care of by incoming equipment, it would appear that this figure is low. We have in St. Louis approximately 100,000 kv-a. in automatic reclosing equipment, which are supplied by automatically switched incoming lines. I believe Kansas City has approximately the same amount.

Mr. Anderson has stated that operating experience has shown that one breaker operating on the ordinary reclosing cycle will reestablish service or lock-out. An additional point, that Mr. Anderson really did not intend to bring into this paper, which might be well worth thinking about, is the reclosing of cable circuits. Usual experience has been that after an outage on a cable, if a single reclosure does not restore service additional reclosures will not do so. It seems we should check up and find out if we would not be better off with oil circuit breakers, etc., if allowed only one closure on cable feeders.

Two different types of line-switching equipment for lines from synchronous sources are mentioned, one being the preferred-emergency equipment used where the lines are of different impedance. Where a feeder is spread out over the city to tap into other stations serving as an emergency feeder for all of them, the reason for making equipment "preferred-emergency" rather than "parallel-line" may be that it is undesirable to overload the emergency source rather than because of different line impedance.

Very frequently, the first step in the city distribution station is the use of preferred-emergency switching on two lines, and the second step would be the parallel operation of the lines. This is something that should be considered when originally designing the stations,—that is, do not design the equipment as suitable only for preferred-emergency service, but keep in mind that, some day, it may be desirable to operate the two lines in parallel.

Mr. Anderson has called attention to *load-responsive* switching of transformer banks. This is a subject that deserves further study, because there are real savings that can be made in taking transformer banks off the line at the time of light load. However we must consider the apparatus, and see that it will not be damaged by standing idle.

Chester Lichtenberg: Three points in Mr. Anderson's paper might be advantageously enlarged upon. On the first page appears the statement: "Consequently, it may be found that different relays are used for automatic operation."

It is a quite common occurrence to have relays applied on the basis of manual-operation experience. Then when the relays fail to function in automatic switching service, the relays are blamed rather than the application. Time and again it is found that relays in automatic stations are required to give a higher degree of service. Nobody is present to substitute for them when they do not function. They must go through their functions completely and of their own account. This hint in Mr. Anderson's paper looms large to those who have had experience in the application of manual relays to automatic station service.

We have preached for a number of years that maintenance and inspection are really the basis of successful automatic operation. Operators who are most successful with them find that a simple system of inspection and maintenance will result in a class of service equal to if not better than most manually operated stations.

The last paragraph in the paper is of even greater importance:

"It has been found advisable to use a separate synchronizing relay combination for each breaker. Different breakers have different closing characteristics, and even though a number of breakers could use a common synchronizing relay, it has been found that the resulting scheme would be more complicated, less flexible, and more expensive than the individual control."

We have tried to combine the necessary functions for each operation in one case or under cover, thereby reducing the number of devices per breaker. This emphasizes Mr. Anderson's point of a more simple system of connections.

O. J. Rotty: (communicated after adjournment) Mr. Anderson describes six different types of automatic switching for the supply lines to a-c. distribution substations. The most desirable type for any particular application depends upon many factors and must be determined for the individual case.

However, it is often desirable in the growth of a station or the development of a system to change the control of the incoming lines from one switching scheme to another. As a rule, this change must be made without any shutdown, and preferably without any crippling of the automatic functions. To accomplish this it is necessary to design the original scheme rather flexibly and as nearly as possible on a "unit" basis.

In the substations at St. Louis, we have adopted a design as standard which provides for two intermediate schemes of control before attaining the ultimate development. The stations are laid out initially for 7500-kv-a. capacity with two incoming lines, either one of which may be made the "preferred line," the other standing by as the "emergency line." They are from sources which may not be synchronous, but are provided with synchronism-check relays to permit tying them together on certain transfer operations. The second step in the development of the stations provides for a capacity of 11,250 kv-a. with the two lines mentioned before operating in parallel. After an interruption, either line is automatically reclosed upon the appearance of synchronous voltage.

The third and final development is for 15,000 kv-a. capacity with three incoming lines, two of which are "preferred" and operating in parallel with the third standing by as the "emergency." The control scheme is laid out so that the change from the first to the second step is carried out by the attachment of two jumpers and the removal of one 2-pole knife switch. The change from the second to the third step requires no additional apparatus nor rewiring of the two original lines and requires only the addition of the apparatus for the third or new line.

In this way it is possible to expand the station with practically no rewiring and with the least possible disturbance to normal operation.

A. E. Anderson: Mr. Hough seems to think that I dropped off a cipher, but I do not think I have. The value might be increased to 750,000 kv-a., or in that neighborhood.

For the protection of cable feeders, we have devised a scheme whereby the value of over-current will determine the reclosing cycle. In case the fault occurs from phase to phase, the particular maximum value of short-circuit current will place a reclosing relay in operation, which gives a certain cycle having longer time intervals than if the fault occurs from phase to ground.

This paper deals with some of the more common forms of incoming line switching. There is practically an infinite number of combinations that might be applied in service, all of which are more or less dependent on the particular conditions of the system, load, and many other factors that are more or less out of the control of the manufacturer.

I believe Mr. Lichtenberg has emphasized sufficiently the point of maintenance and characteristics of relays for automatic switching equipment. The types of equipment described in the paper are more or less flexible, some of the basic schemes—at least, we consider them basic—we can elaborate on and take care of a large number of combinations. It takes just a slight departure, here and there, in most cases, to give the desired operation.

Improvements in Moderate Capacity Oil Circuit Breakers

BY J. B. MacNEILL¹

Associate, A. I. E. E.

Synopsis.—The increased duty requirements of power station service require circuit breaker design to give maximum interrupting capacity in a minimum of space. Compact, relatively high-power breakers having all three poles in a single round tank have been designed, which, in addition to increase in the rating for a given space, give improved performance over types previously available.

The relations of the current-carrying loops inside the breaker and the diversity factor afforded by the common oil volume and air space give superior results in operation. This type of design permits use in current ranges where decreased arc energy, as compared to power handled, can be secured.

* * * * *

THE desirability of getting increased circuit-breaking capacity in a given space arises frequently in rapidly growing power systems. There have been many cases where the oil circuit breaker has been the "neck of the bottle" in limiting power that can be handled on a switch house layout. The bus itself, disconnecting switches, and other elements may be entirely adequate to handle increased power, but the circuit breaker may present severe limitations.

It is only natural that operators and manufacturers alike should be interested in the development of an oil

on high-power multiple breakers. A round tank is not in itself essential; in fact, any tank giving proper clearances and strength is sufficient. However, the ease with which necessary strength with minimum material can be obtained in a round tank with a dish bottom and a dome-shape cover, will be obvious.

In the past, objections have been raised in this coun-

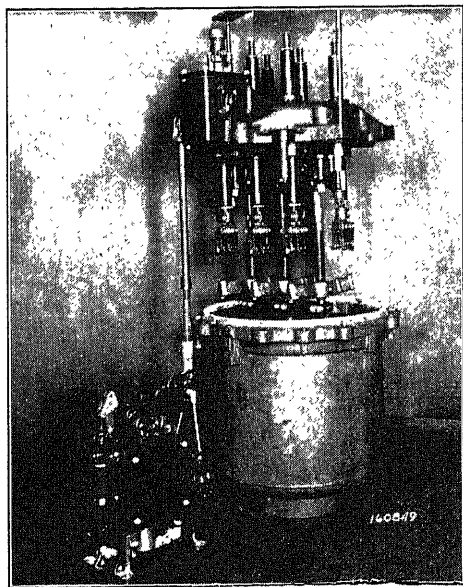


FIG. 1—THREE-POLE BREAKER IN SINGLE ROUND TANK SHOWING CONDENSER TERMINALS, CONTACTS IN OPEN POSITION, TANK REMOVED, AND ELECTRIC OPERATING MECHANISM

circuit breaker to handle a maximum power in a minimum of space. To do this, it is obvious that the combination of a three-pole breaker in a single round tank should receive consideration because of the possibilities of embodying in such a type the features that are used

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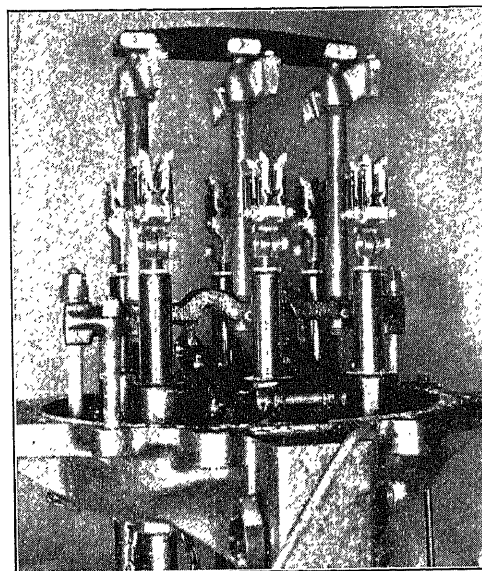


FIG. 2—THREE-POLE CIRCUIT BREAKER IN SINGLE ROUND TANK SHOWING CONTACT AND CROSS-BAR CONSTRUCTION WITH TANK REMOVED

try to the idea of multiphase switching in a single tank where considerable power is used. Many operators preferred isolation of the pole units from each other in separate cells so that in case of failure of one pole, fire and oil throw would have less chance to involve other phases. There was also the thought that when several phases were handled in a common volume of oil the chances for arcs getting together were increased. Manufacturers have, therefore, not found it generally desirable to depart from the conventional multiple single-pole arrangement for high-power work, because by so doing they would have to handle two types where one would do the work.

Recently, however, there has been an increasing

number of stations where space is at a premium or where cell structures have already been built and are too small to allow ordinary breakers to handle present power demands. There has also been a demand in the smaller capacities for breakers that throw minimum amounts of oil and gas and, where the outlet of the breaker can be piped away from the structure with assurance, that such oil and gas will not be released in the cell structure itself.

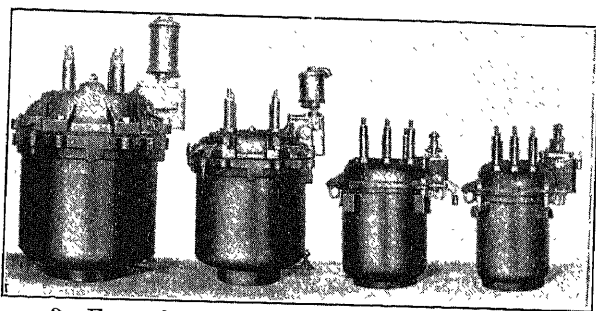


FIG. 3—FOUR SIZES OF THREE-POLE SINGLE-THROW OIL CIRCUIT BREAKERS HAVING ALL POLES IN SINGLE CYLINDRICAL TANK

The breaker shown in Figs. 1 and 2 was designed in 1922 to take care of the type of service referred to. It is a 20-in. diameter, round tank three-pole breaker embodying in a small space the general features of high-power breaker construction. The tank structure has

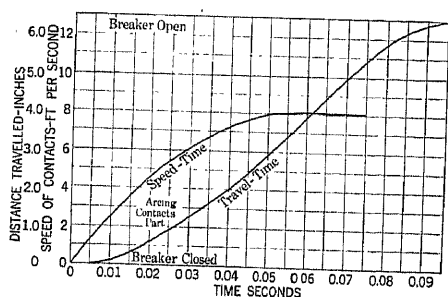


FIG. 4—SPEED OF TRAVEL CURVES OF THREE-POLE SINGLE-THROW BREAKER IN ONE ROUND TANK

a high ultimate strength resulting from steel construction throughout. It is equipped with a muffling device to separate the oil from the gas as it leaves the tank structure, and so arranged that the gas can be piped away—thus preventing the possibility of gas explosions in the switch cell.

The type of design shown in Figs. 1 and 2, after extensive factory and field tests on the 20-in. tank size, gave promise of extension to other capacities; and a line of circuit breakers comprising four tank sizes is shown in Fig. 3, with ratings as follows:

Inside diameter of tank	Amperes at rated voltage	Approximate arc kv-a.
16 in.	7,500 at 7,500 volts	100,000
20 "	5,000 at 15,000 "	130,000
26 "	8,000 at 15,000 "	200,000
32 "	14,000 at 15,000 "	350,000

The performance of a breaker depends upon two principal factors. The first of these is the amount of energy released in the structure when opening short circuits, which may be called the energy, or duty factor. The second is the ability of the structure provided to take care of this energy after it has been formed, which might be called the structure factor. The energy factor

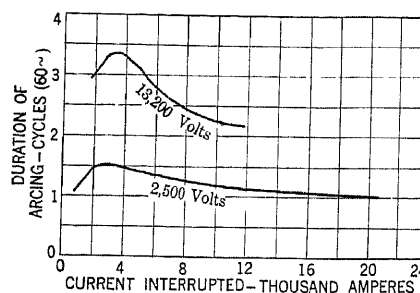


FIG. 5—CURVES SHOWING DURATION OF ARCING WITH CURRENT INTERRUPTED AT DIFFERENT VOLTAGES

is represented by the integrated kilowatt-seconds obtained from the short-circuit current oscillograph record and the arc-voltage oscillograph record. The relationship of arc energy to short circuit kv-a. varies greatly with different designs of circuit breaker and also with different conditions of operation on the same circuit breaker structure.

A high-voltage circuit breaker handling small currents on short circuits has an entirely different ratio of arc energy to short circuit kv-a., than that of a low-voltage breaker handling high currents on short circuits.

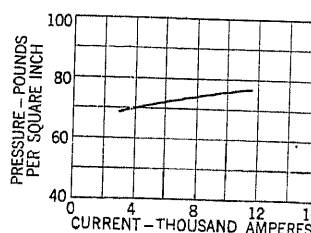


FIG. 6—TANK PRESSURE VARIATION WITH CURRENT INTERRUPTED ON THREE-PHASE, 60-CYCLE, 13,200-VOLT UNGROUNDED SHORT CIRCUITS. THREE-POLE BREAKER IN ONE ROUND TANK

Likewise a breaker designed for, say, 15,000 volts will have a different ratio when operated at 2500 volts. A knowledge of the variations of arc energy with short circuit kv-a. is necessary to the successful design of a line of circuit breakers. This is especially so because facilities for testing the largest breakers do not exist and their design depends on extrapolating results obtained on smaller sizes.

Figs. 5 to 14, inclusive, show various operating characteristics of the multiple breaker in a common

round tank when opening three-phase short circuits on a 60-cycle, ungrounded neutral system.

In Fig. 5 is shown the relationship between short circuit amperes and cycles of arcing at 13,200 volts and 2500 volts for a given breaker structure of the type under discussion. This is simply a curve of averages and is subject to considerable variation between successive short circuits. It serves, however, to indicate

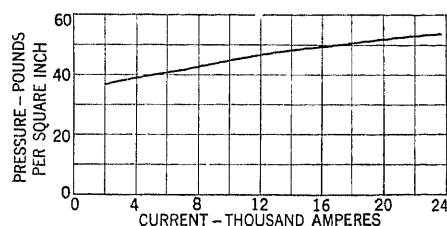


FIG. 7—CURVE SIMILAR TO THAT IN FIG. 6, FOR 2500-VOLT SERVICE

the general relationship between duration of an arc and the amount of current in the arc. The shape of this curve is affected by speed of parting of the contacts, the number of breaks in series per phase, the magnetic blow-out effect of the current-carrying loop, the spacing between the arcing contacts and the tank liners, and to

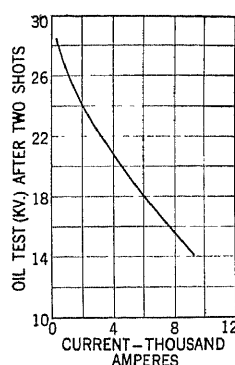


FIG. 8—OIL TEST—THREE-POLE BREAKER IN ONE ROUND TANK AFTER OPENING THREE-PHASE, 60-CYCLE, 13,200-VOLT UNGROUNDED SHORT CIRCUITS

some extent on the head of oil over the contacts and the volume of the air-chamber. From the point of view of the system connected to the breaker, the shape of this curve depends on the restored voltage, whether the neutral is grounded at the short circuit as well as at the machine, the power factor during the short circuit, and other considerations.

It has been found, however, that for 15,000 volts (and below, especially) curves of the general shape shown in Fig. 5 are secured under different conditions of system and breaker characteristics.

In Fig. 5 it is noticeable that the time of arcing for large currents is less than that with relatively small

currents. The arcing time increases for a while with current, but there comes a point where this time begins to diminish rapidly, and finally the curve becomes practically asymptotic. The position of the high part of this curve depends on the magnetic blow-out action on the arcs. The type of breaker shown keeps the high point of the curve at lower current values than do some other types, because the current-carrying loops are closer together and the magnetic blow-out effects, in general, are greater. It will be obvious that a lower time of arcing at high currents results in a reduction in the arc energy dissipated in the breaker and resulting oil throw, contact depreciation, and stresses which the structure has to withstand.

Curves in Fig. 13, showing single-phase arc energy as a function of current interrupted, are of interest. For the particular case, the arc energy varies almost directly as the short circuit current but differs greatly for the different voltage classes. This is readily seen from the differences in arcing times shown in Fig. 5.

An interesting relationship is that between kilowatt-

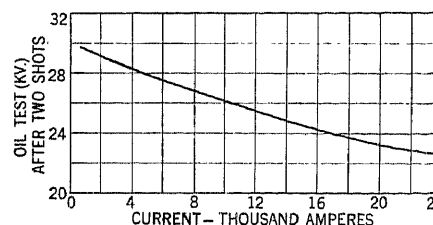


FIG. 9—CURVE SIMILAR TO FIG. 8, EXCEPT FOR 2500-VOLT CIRCUITS

seconds dissipated in a breaker and the kv-a. of the short circuit interrupted by it. From Fig. 13 we find that for 13,200 volts the three-phase kilowatt-seconds of arc energy is 0.0035 of the three-phase short-circuit kv-a. As an illustration: at 6000 amperes the arc energy for 13,200 volts is 160 kilowatt-seconds per phase.

The relation $\frac{\text{Arc energy in kilowatt-seconds}}{\text{Kv-a. interrupted}}$

$$= \frac{3 \times 160}{13.2 \times 6000 \times \sqrt{3}} = 0.0035$$

In the same way, for 2500 volts the ratio is 0.0049. Accordingly, there is more energy lost per kv-a., in a breaker of this particular design, on low voltage, such as 2500 volts, than on 13,200 volts. With other designs of breaker this relationship may not hold, and the factors of arc energy related to kv-a. in the short may be quite different.

Several articles have been written on this general matter and it is interesting to note comparable results. Mr. P. Charpentier in the *Rev. Gén. Elec.*, May 14, 1921, developed a formula for arc energy in terms of circuit voltage, short-circuit current, and time of arcing in

which he assumed that time of arcing varied directly with voltage for a given velocity of contacts. According to Charpentier's formula a breaker of this design opening 6000 amperes, three phases on a 13,200-volt circuit would have a factor of 0.0031 as the relationship between arc energy and short-circuit kv-a. This is in close agreement with the similar factor derived from the data here presented.

However, for short circuits of similar kv-a., on lower

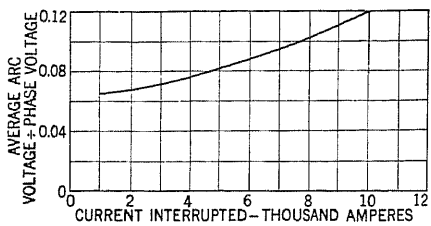


FIG. 10—VARIATION OF AVERAGE ARC VOLTAGE TO PHASE VOLTAGE RATIO WITH RESPECT TO CURRENT INTERRUPTED, 13,200-VOLT, 60-CYCLE UNGROUNDED CIRCUITS

voltages this agreement does not hold. The average ratio for 2500-volt circuits (taken from data on Fig. 13) is 0.0049, while Charpentier's formula would give a ratio of 0.0006. This wide discrepancy is accounted for by the fact that arc energy as shown in Fig. 13 is rather directly a function for this particular breaker of short-circuit currents, and arc voltage at the high currents secured with low-voltage short circuits is a considerably greater proportion of line voltage than it is for higher voltage circuits. This is borne out by Figs. 10 and 11. From Fig. 10 we find that for 13,200 volts the average arc voltage at 6000 amperes is

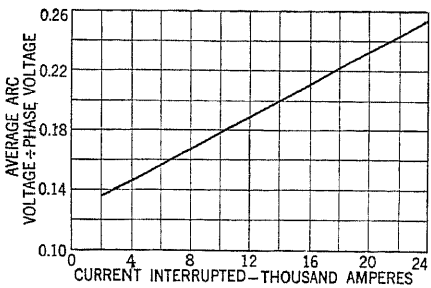


FIG. 11—CURVE SIMILAR TO FIG. 10, EXCEPT FOR 2500-VOLT CIRCUITS

approximately 8 to 9 per cent of phase voltage, whereas for similar kv-a. at 2500 volts the average arc voltage is approximately 25 to 30 per cent, as indicated by Fig. 11.

In the development of the line of breakers shown in Fig. 2 an unusual amount of short-circuit testing has been possible. In 1923 the Detroit Edison Company cooperated in the development and testing of the 20 in. tank size. At their Delray Station currents as high as 25,000 amperes at 4800 volts were handled successfully, and with much less signs of stress on the structure

than on conventional forms of breakers of larger physical size. Afterward a 40,000-kv-a., 10-per cent reactance factory test plant became available, and exhaustive series of tests have been made.

It has not been possible to destroy or seriously damage the 20-in. size on the 40,000-kv-a. test set. The ability of the larger sizes, therefore, for the present must remain a matter of extrapolation. We know that the general characteristics of a small size for available test conditions is as shown in Fig. 13. The larger sizes can be tested, of course, within present power limitations. From such test data and knowledge of general characteristics it is estimated that the larger sizes are conservatively rated.

The intimate relationships between current carrying

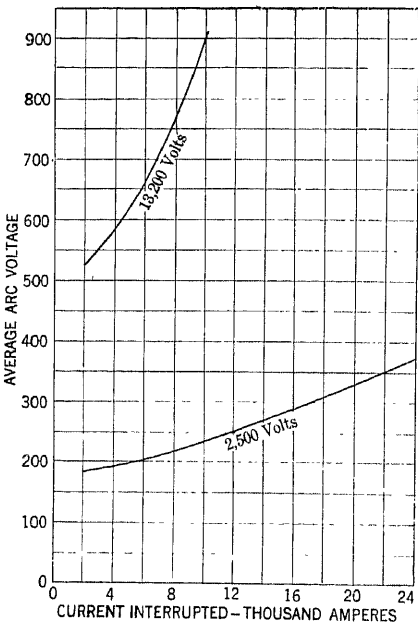


FIG. 12—RELATION OF AVERAGE ARC VOLTAGE TO CURRENT INTERRUPTED FOR THREE-PHASE, 60-CYCLE UNGROUNDED SHORT CIRCUITS. THREE-POLE BREAKER IN ONE ROUND TANK

loops in this type of breaker involved recourse to certain special design features. On currents of 40,000 to 50,000 amperes it was found that ordinary, porcelain terminals would shatter under the blows imposed upon them by the reaction of the loops. It was necessary to use a terminal insulation, having mechanical strength and at the same time sufficient flexibility to prevent breakage. The condenser type terminals with heavy ground band and clamp construction, as shown in the illustrations, seemed most desirable.

A similar mechanical action took place between the moving contacts at high currents. During one test made, with current rushes of 60,000 to 70,000 amperes at 4800 volts on the 20-in. tank size, the circuit was ruptured not by the opening of the breaker in the ordinary way, but by the fracture of the lifting rods causing the moving contacts to be thrown violently into the bottom of the tank. The circuit was ruptured with

approximately one-half cycle of arcing on 60 cycles and represents one more of those cases where the operation was successful but the patient died. It was found desirable to strap the moving contact elements together where heavy currents at the lower voltages were involved.

The question frequently is asked whether the mechanical speed of operation of a breaker is seriously affected by the short-circuit current flowing through it. Mechanical strains on contact parts due to mechanical blow-out effects are a function of the square of the current. Fig. 14 shows the speed of operation of a breaker such as referred to with varying currents being interrupted. The general conclusion may be drawn that for small structures having close mechanical loops this effect becomes noticeable around 15,000 amperes and increases in effect fairly rapidly with current increase beyond that point.

There are certain diversity factors about this type of breaker that will interest an operating man. The oil volume and air volume are common to the three poles. Since by far the greater number of short circuits is single phase, the total oil volume will not depreciate as fast as though the single-phase short circuit had been on one-third of the oil, which would be the case with a multipole breaker having separate tanks. Also, the common air volume tends to diminish the shock to the breaker structure that occurs on single-phase short circuits, so that while the maximum pressure to which

A careful analysis of test data is necessary in formulating ratings. Actual operating conditions vary from test conditions. Over the life of a breaker operating speed may vary somewhat, the condition of the oil will change at times, and certain circuit conditions will be

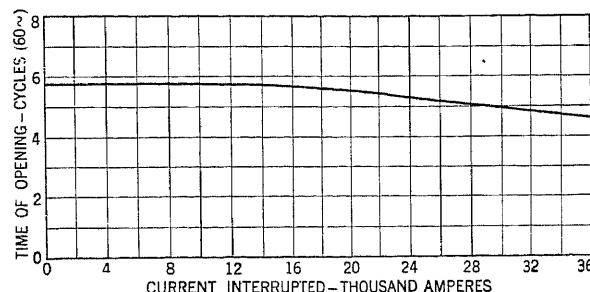


FIG. 14—RELATION OF TIME OF OPENING FROM BEGINNING OF MOVEMENT UNTIL COMPLETION OF STROKE AGAINST CURRENT INTERRUPTED. THREE-POLE BREAKER IN ONE ROUND TANK

found much harder on a breaker than others. With a general understanding of the operating characteristics of a breaker, test data can be properly evaluated and a rating given that will be conservative and insure satisfactory operation.

Discussion

R. R. McGee: As Mr. MacNeill has brought out, oil circuit breakers of minimum size for moderate interrupting capacity and moderate voltage are constantly assuming greater importance. Operators are demanding breakers which are safe and reliable, and which will occupy the minimum of space and require the minimum of maintenance attention.

As a result of this increasing demand the writer's company has applied to a new round-tank breaker many of the electrical and mechanical principles of design essential to the larger breakers.

Among the design features essential to the attainment of high interrupting capacities are: the internal unit mechanism, oil-separating chambers and gas vents, round tanks with dome covers, and ample mechanical strength. All of these features are to be found in the new round-tank breaker for moderate interrupting capacity. The internal mechanism, of course, prevents contact reclosure due to unbalanced pressures acting on the mechanism; the separating chambers and gas vents provide adequate relief for the gases without permitting oil throw; and by proper design of the round tank with its dome cover ample mechanical strength is secured.

The moderate-duty breaker employs one tank for all three phases with considerable saving of space.

The top frames are dome-shaped because this construction, together with the use of a round tank, eliminates distortion. The heavy, bulky, and expensive castings formerly used have been replaced by the lighter but stronger boiler-plate construction.

The contacts of this new moderate-capacity breaker are of the wedge-and-finger construction. The stationary contact fingers are the so-called wide-angle fingers. They are self-aligning, and their contact surfaces are at all times maintained parallel to the contact surfaces of the blade, thus assuring maximum contact. Extended fingers and a removable section of the blade are used to bear the brunt of the arcing, protecting the main contact sur-

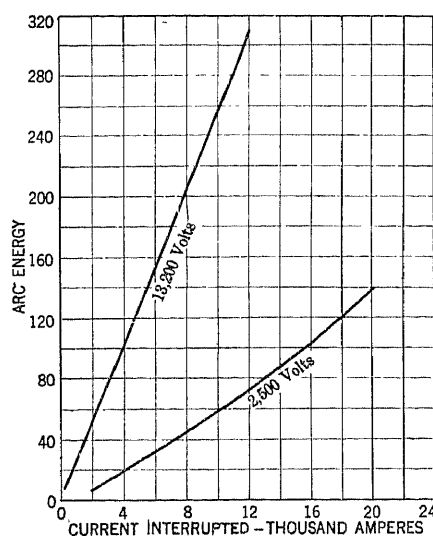


FIG. 13—RELATION OF ARC ENERGY PER PHASE TO CURRENT INTERRUPTED ON 60-CYCLE UNGROUNDED CIRCUITS. THREE-POLE BREAKER IN ONE ROUND TANK

the breaker may be subjected may be considerable, yet the average pressure under operating conditions will be reduced. In general, it is felt that less maintenance for a given duty will be obtained with this form of breaker than with a multiple, single-pole breaker, and also that the maintenance is more easily and quickly performed.

faces. Contacts of this same type are employed in the plain-break breakers of larger size and are also used in many cases to supplement the explosion-chamber contacts.

There is a little similarity however, between the bushings which support the contacts. In the smaller breaker, designed only for moderate voltages and for indoor service, bushings of Herkolite surround the central conductor. The assembled bushings are individually removable from the frame. In the larger breakers where higher voltages are encountered, compound- or oil-filled porcelain bushings are used.

Of course there is a wide difference in the application of the several breakers which have been described. The moderate-capacity breakers referred to are built for 7500- and for 15,000-volt service, 400- to 3000-ampere current ratings, with interrupting capacities ranging from 100,000 to 250,000 kv-a., in accordance with N. E. M. A. standard steps, as determined by the

selection of a 16-in. to 32-in. tank. The new line of large indoor oil circuit breakers has voltage ratings of 15,000, 25,000, or 37,000 volts, with normal currents up to 4000 amperes. Here the interrupting capacities vary from 350,000 to 2,000,000 kv-a., with tanks ranging from 16 in. to 36 in. in diameter. The round-tank breakers for outdoor service are built for all standard voltages from 15,000 to 220,000 volts, and may be obtained with either finger-and-wedge, or explosion-chamber contacts, except above 154,000 volts where explosion chambers only are used. Interrupting capacities from 350,000 to 750,000 kv-a. can be obtained from the plain-break breakers. When explosion chambers are used, interrupting capacities from 750,000 to 2,500,000 kv-a. are available. The tanks are mounted directly on the foundation for higher voltages, and with this mounting manholes are provided to afford inspection of the internal parts.

The Vibration of Transmission-Line Conductors

BY THEODORE VARNEY¹

Associate, A. I. E. E.

Synopsis.—This paper is a continuation of a former one by the writer in May, 1926.

Records are given of vibration in actual transmission lines under widely varying conditions and with various conductor materials. These observations indicate the limiting values of wavelength frequency and amplitude of such vibrations encountered in service.

Laboratory experiments are described in which the observed conditions were artificially reproduced in a large conductor. The stresses adjacent to a point of support were studied with the aid of a microscope. The wave shape was plotted and the energy required to maintain vibration was recorded.

All conductor vibration breaks observed in practise have occurred at supports or badly made joints. The conclusion is reached that if the radius of curvature at the support can be maintained at least equal to that at the center of a loop, no breakage will occur.

Mathematical expressions are given for determining the radius of curvature at the center of a loop, the bending moment at a support, and the necessary additional amount of conductor stiffness at the support to satisfy the desired condition.

A simple form of stiffening device is described which even in a more crude form has been found effective in several cases of actual service.

IN the previous paper² the writer discussed the action of the wind on a suspended conductor and gave rules for determining the wavelength and frequency of the resulting vibrations.

Since the date of that paper, records have been kept of the wind action upon a large number of transmission lines equipped with different kinds of conductors and installed under various conditions. Typical cases selected from these data are listed in Table I.

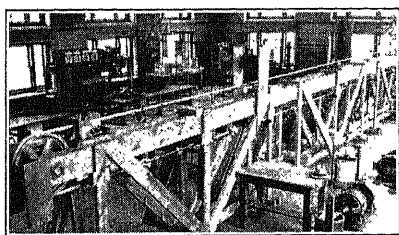


FIG. 1—FRAME FOR TESTING VIBRATION OF CONDUCTOR

Experimental apparatus was next installed at the Carnegie Institute of Technology at Pittsburgh by means of which certain of the data observed in the field could be reproduced in a particular conductor of large size.

This apparatus consisted of a heavy wooden frame provided with grooved pulleys at each end. The distance between centers of pulleys was 50 ft. and tension was maintained by turnbuckles and a dynamometer installed in the lower side of the conductor loop.

Vibrations were produced and maintained by an $\frac{1}{8}$ -hp., 110-volt d-c. motor, operated from a storage battery. The motor was located 6 ft. from one end of the span and was belted to a small counter shaft carrying a flywheel, a tachometer, and a crank disk. The latter was arranged to receive a wrist pin at varying radii, and which in turn engaged with a light wooden

connecting rod and guided plunger. This plunger was connected with the conductor by means of a small spiral tension spring. The travel of the plunger was adjusted to $1\frac{1}{2}$ in. when the spring tension varied from $\frac{3}{4}$ to 4 lb.

The field of the motor was separately excited and held constant. The armature speed was controlled by an adjustable resistance. The power consumed was so small that the speed of the motor could be held constant and the conductor maintained in resonant vibration continuously. By varying the speed, one, two, three, and four loops could be obtained.

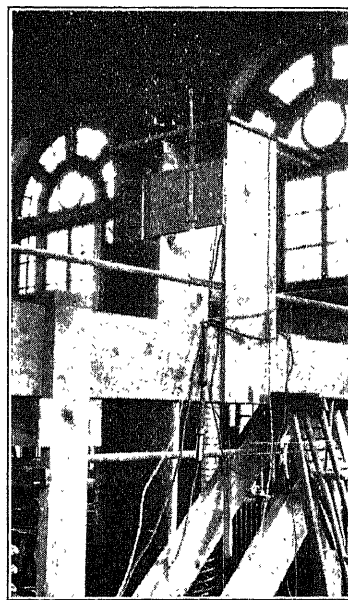


FIG. 2—SHOWING METHOD OF VIBRATING CONDUCTOR

Table II gives conductor tension, loop length, amplitude, frequency, and watts input to motor when vibrating the conductor and when disconnected. The power consumption is inconsistent as will be noted by the fact that in some cases it is less when connected than when disconnected. This is believed to indicate that the friction losses were variable and large compared to the

1. Aluminum Company of America, Pittsburgh, Pa.
2. Notes on the Vibration of Transmission-Line Conductors, TRANS. A. I. E. E., 1926, p. 791.
Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.

TABLE I
EFFECT OF WIND ACTION ON TRANSMISSION LINES—TYPICAL CASES

NOTE: Columns 11 to 19 are included for cases a to c at the foot of the Table

1	2	3	4	5	6	7	8	9	10
Cond.	Diam. in.	Weight per ft. (lb.)	Span (ft.)	Sag (ft.)	Temp. (Fahr.)	Wind (M. P. H.)	Loop (ft.)	Frequency (Cy. P. S.)	Amp. 1/32 inch
(a) ACSR	1.246	1.332	800	11.5	80	2.6	15.0	16.5 —	26
"	"	"	"	11.8	90	4.1	20.7	11.0	6
"	"	"	"	10.9	64	4.5	15.0	15.3	20
"	"	"	"	11.5	80	4.6	14.5	17.5	8
"	"	"	"	11.4	78	5.0	20.1	9.1	6
"	"	"	"	11.2	68	5.5	20.0	13.1 —	24
"	"	"	"	11.7	88	5.7	13.5	13.8	20
"	"	"	"	11.7	88	6.0	14.5	16.1	18
"	"	"	"	11.0	66	6.1	16.3	14.4	18
"	"	"	"	11.2	68	6.1	20.0	14.6	12
"	"	"	"	10.9	64	6.9	34.5	9.3 —	18
"	"	"	"	11.0	66	7.1	31.0	7.3	8
"	"	"	"	10.9	64	7.3	33.0	8.4	20
"	"	"	"	11.8	90	9.5	13.5	15.3	12
ACSR	1.093	1.024	1000	22.7	— 2	7.0	17.5	12.0	14
"	"	"	"	25.0	26	7.2	16.0	10.0	12
"	"	"	"	23.8	— 1	10.0	14.0	9.2	6
"	"	"	"	23.8	10	10.0	12.0	10.8	6
"	"	"	"	24.5	20	10.0	11.0	6.4	4
"	"	"	"	13.9	20	2.0	16.5	8.2	20
"	"	"	"	13.2	8	2.6	25.0	7.3	24
"	"	"	"	12.3	—22	4.5	15.0	7.0	32
"	"	"	"	13.9	18	5.5	25.0	7.7	6
"	"	"	"	14.0	14	6.2	20.0	11.1	24
"	"	"	"	14.4	15	9.0	14.5	10.3	24
"	"	"	"	12.9	— 6	12.0	13.5	15.4	22
"	"	"	"	14.7	18	13.2	15.0	14.3	4
ACSR	"	"	921	20.0	32	2.8	24.0	8.5	28
"	"	"	"	20.0	30	2.9	24.0	10.5	14
"	"	"	"	19.8	30	4.7	16.0	11.4	16
"	"	"	"	19.8	30	4.7	16.0	11.3	14
"	"	"	"	19.8	30	4.7	16.0	10.7	22
"	"	"	"	19.6	24	5.8	12.0	11.9	12
ACSR	"	"	781	18.9	48	1.0	18.9	8.6	8
"	"	"	"	19.4	56	1.4	15.8	10.0	15
"	"	"	"	18.8	46	2.9	43.5	11.0	17
"	"	"	"	18.9	48	3.2	27.4	11.0	16
(b) " "	"	"	"	18.9	48	3.3	14.3	9.3	24
"	"	"	"	18.9	48	3.4	20.3	8.5	6
"	"	"	"	18.7	44	4.3	39.0	7.0	14
ACSR	1.000	0.858	1200	20.2	78	3.5	13.0	19.7	10
"	"	"	"	20.5	70	3.9	21.7	13.0	28
"	"	"	"	20.5	70	5.2	24.5	10.5	12
"	"	"	"	20.5	70	5.6	24.2	12.0	20
"	"	"	"	20.5	70	8.0	14.7	20.0	4
(c) " "	"	"	"	18.2	50	8.0	18.9	15.0	24
"	"	"	"	18.2	51	8.9	14.5	18.3	24
"	"	"	"	18.2	50	10.0	12.8	21.0	14
"	"	"	"	20.5	70	19.1	12.2	23.0	6
"	"	"	"	20.5	70	22.5	12.3	22.5	8
ACSR	1.000	0.858	984	13.9	70	5.0	15.9	15.9	8
"	"	"	"	13.9	70	5.7	15.6	13.0	8
ACSR	0.953	0.779	792	17.6	59	2.2	12.4	16.3	4
"	"	"	"	17.6	59	3.8	8.9	12.3	6
"	"	"	"	17.6	58	4.0	11.9	10.5	4
"	"	"	680	14.1	65	4.0	12.0	15.0	6
"	"	"	"	14.0	64	4.9	12.0	15.4	4
"	"	"	"	14.2	67	5.5	12.0	15.0	3
"	"	"	"	14.2	68	7.1	12.0	15.5	4
"	"	"	650	11.6	58	0.1	27.6	6.9	17
"	"	"	"	11.6	58	0.5	44.6	5.4	10
"	"	"	"	11.6	58	0.8	23.3	6.9	19
"	"	"	"	11.6	58	1.7	26.0	9.0	9
"	"	"	"	11.6	58	2.6	37.7	5.3	6
"	"	"	"	11.6	57	4.9	12.3	10.0	4
"	"	"	"	11.6	58	5.7	11.2	15.3	4

TABLE I—Continued
EFFECT OF WIND ACTION ON TRANSMISSION LINES—TYPICAL CASES

NOTE: Columns 11 to 19 are included for cases *a* to *e* at the foot of the Table

1	2	3	4	5	6	7	8	9	10	
Cond.	Diam. in.	Weight per ft. (lb.)	Span (ft.)	Sag (ft.)	Temp. (Fahr.)	Wind (M. P. H.)	Loop (ft.)	Frequency (Cy. P. S.)	Amp. 1/32 inch	
(d)	"	0.904	0.783	725	17.7	35	4.2	18.0	19.7	24
	"	"	"	"	14.3	0	5.4	15.0	15.8	20
	"	"	"	"	13.9	-11	5.7	15.0	15.8	20
	"	"	"	"	14.5	5	5.8	15.0	15.8	20
	"	"	"	"	15.8	16	9.1	9.5	25.0	24
	"	"	"	"	16.9	38	10.2	14.0	19.7	24
	"	0.806	0.622	1000	23.4	46	4.8	16.4	—	2
	"	"	"	975	22.2	46	3.4	15.0	12.0	4
	"	"	"	"	22.2	46	5.7	14.5	11.8	17
	"	0.741	0.527	750	16.9	62	3.8	18.2	9.5	12
	"	"	"	"	16.7	59	4.9	12.3	18.5	9
	"	"	"	"	17.1	69	5.7	11.6	13.4	14
	"	"	"	"	16.8	60	6.8	12.3	16.3	7
	"	"	"	"	17.0	67	7.4	11.5	—	6
	(e)	ACSR	0.633	0.343	1020	19.8	54	4.9	4.0	30.0	4
"		"	"	"	24.5	58	6.8	9.5	22.3	4
"		"	"	"	26.2	70	8.5	12.0	17.2	6
"		"	"	"	26.2	70	8.5	14.0	12.0	10
"		"	"	"	26.2	70	14.8	4.0	45.0	2
"		"	"	920	15.3	18	1.1	20.0	13.6	6
"		"	"	"	17.0	37	5.5	10.0	22.0	6
"		"	"	"	19.7	59	6.8	8.5	28.0	3
"		"	"	"	16.0	28	9.1	8.8	26.0	4
"		"	"	"	19.6	48	11.4	6.0	35.0	5
"		"	"	"	18.1	42	14.8	4.2	52.0	1
A. C		0.724	0.373	880	15.7	50	5.2	11.1	20.3	16
"		"	"	"	15.7	50	5.7	11.9	20.0	21
"		"	"	"	15.7	50	4.8	12.4	21.0	18
"		"	"	860	14.9	57	1.1	18.8	18.8	10
"	"	"	"	14.7	56	2.3	22.8	15.0	14	
"	"	"	"	14.7	57	4.6	11.2	14.5	26	
"	"	"	"	14.7	57	6.2	9.4	16.0	13	
"	0.586	0.251	752	11.6	54	3.8	9.0	—	4	
"	"	"	"	11.6	54	5.5	9.0	—	2	
"	"	"	"	11.6	54	8.5	5.9	—	4	
"	"	"	583	10.9	55	1.0	14.0	11.8	9	
"	"	"	"	11.2	57	2.6	10.6	12.0	3	
S. C.	0.528	0.653	750	14.4	58	4.9	6.9	25	6	
"	"	"	"	14.4	58	6.8	6.9	32	6	
"	"	"	699	12.3	54	4.3	5.9	15.5	4	
"	"	"	"	12.3	54	7.2	4.0	—	1	
"	"	"	"	12.3	56	8.5	6.0	—	2	
"	"	"	"	12.3	54	9.2	6.0	—	12	
"	"	"	"	12.3	54	9.8	3.0	—	1	
S. S.	0.500	0.520	680	6.9	58	3.4	13.0	19	6	
"	"	"	"	6.9	58	3.6	10.3	20	4	

11	12	13	14	15	16	17	18	19
Tan. Q	P	R (ft.)	$Y'' - Y'$ (in.)	K (in. — lb.)	$I_a M_a + I_s M_s$	$R K$	$I_d M_d$ Required	I_d Required ($M_d =$ 29,000,000)
(a) 0.00709	9270	674	0.1390	1290	811,733	10,433,520	9,621,787	0.331,786
(b) 0.00687	4150	663	0.1280	531	478,763	4,225,836	3,747,073	0.129,209
(c) 0.00677	8500	682	0.1283	1091	337,173	8,929,236	8,592,063	0.296,278
(d) 0.01033	3260	292	0.1381	451	233,947	1,580,304	1,346,397	0.046,427
(e) 0.00604	2350	590	0.1863	438	87,127	3,102,240	3,015,113	0.103,969

NOTE: ACSR = Aluminum Cable Steel Reinforced.

A. C. = All Aluminum Cable.

S. C. = Stranded Copper.

S. S. = Stranded Steel.

energy consumption of the vibrating conductor. The small power required is noteworthy in view of the fact that the conductor in this case was 1.093 in. diameter, weighed 1.024 lb. per ft., and in some cases was under a tension of 9000 lb.

In order to obtain definite conditions at the point of support, a heavy cast-iron block was bolted to the framework near one of the pulleys. This block held a split steel bushing bored out to fit the conductor accurately and tightly. The distance from the end of this bushing to the center of the other pulley was exactly 48 ft.

A high power microscope was bolted to this block so that no relative motion between them existed. The microscope was then focused on the top of the conductor next to the end of the bushing. By means of an eyepiece micrometer the maximum longitudinal motion of a point on the top strand of the conductor was observed to be approximately 0.000656 in. with a tension of 9000 lb. The path of the observed point diminished longitudinally as the microscope was rotated from the top toward the side of the conductor, becoming more and more oblique and approaching a right angle with the

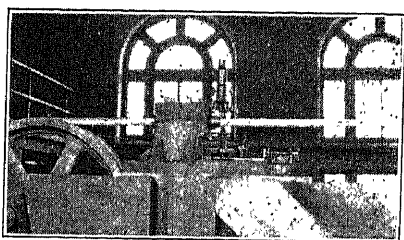


FIG. 3—CAST-IRON BLOCK ON TEST FRAME

longitudinal axis of the conductor on the horizontal transverse diameter. This last condition was due to the transverse motion of vibration and indicates that the strand fibres on the side are not subjected to pulsating longitudinal stresses as are those on the top and bottom of the conductor. No effect of longitudinal vibratory impact could be discerned and the effects noted above are undoubtedly due to simple transverse bending in the vertical plane. The transverse motions of the conductor were carefully noted and plotted. The resulting curves are sine waves for all loops not adjacent to a support. The supports distort the wave, producing a bending action adjacent to it and a point of inflexion in the first half of the loop.

In all of the cases recorded in Table I, no breakage of strands has occurred except adjacent to a support or at a joint which had been either poorly designed or applied. It is a logical conclusion that if means can be found to prevent any sharper bending of the conductor at a support or at a joint, than occurs at the middle point of a loop, breakage due to vibration will be prevented.

Considerable thought and ingenuity have been expended upon the design of suspension clamps, but so far as the writer is aware no logical method has previously been developed to determine the proper shape

of the conductor seat. The support cannot be regarded as a simple node and it is difficult to provide effective means for permitting the wave to pass through the suspension clamp without bending the conductor. The reason for this is that it is impossible always to have a wave impulse leaving on one side of a support at the instant it is arriving on the other. This is evidenced by recorded cases of broken strands while the conductor rested on a sheave.

TABLE II.

Conductor..... 795,000 cm. ACSR (54 Alum. 7 St.)
Wt. per ft..... 1.024 lb.
Diameter..... 1.093 in.
Span..... 48 ft.

Tension lb.	Loop length ft.	Amplitude in 1/32 in.	Frequency cycles per sec.	Watts connected to conductor	Watts dissipated from conductor
5500	48	112.	4.27	8.10	6.75
5500	24	56.	8.43	18.35	15.75
5500	16	30.	12.67	27.01	27.15
5500	12	20.	16.87	37.44	40.50
7500	48	104.	4.87	10.05	7.90
7500	24	32.	9.67	21.00	18.80
7500	16	24.	14.33	34.03	32.10
7500	12	20.	19.13	46.87	48.30
9000	48	102.	5.33	10.73	8.80
9000	24	18.	10.60	21.70	21.30
9000	16	16.	15.67	34.20	36.50
9000	12	12.	20.87	52.20	54.40

If the suspension clamp could be designed with a radius as large as that at the loop center it would be effective but it is difficult to do this within available limits of design. The angle of the conductor with the horizontal in a span of the greatest practicable length and sag at present in use, or contemplated, is about 23 deg. The summer to winter variation would be on the order of 2 deg. or 3 deg. while the vibration angle is less than $\frac{1}{2}$ deg. The correcting means must therefore be applied to the moving conductor.

A simple and practical method is to apply to the conductor a layer of cylindrical rods at the support. Preferably each rod tapers at each end, thereby enabling it to be twisted around the conductor and held at the ends. This gives maximum resistance to bending at the support and a tapering mass on each side to prevent sudden reflection of waves at its ends. This arrangement is illustrated in Fig. 4.

The above conclusions are based upon the observations and experiments described and also upon the following theory. Referring to Figs. 5 and 6, the letters have the following meanings:

- L = Loop length = half wavelength
- A = Amplitude of complete vibration
- R = Radius of curvature at middle point of loop
- Q = Angle with axis at node point of freely vibrating loop
- F = Frequency of vibration in cycles per sec.
- V = Velocity of transverse wave in ft. per sec.
- P = Total tension in conductor in lb. (conductor not vibrating)
- l = Arc-length of loop

- W = Weight per ft. of conductor in lb.
 G = Acceleration due to gravity = 32.2 ft. per sec.
 K = Moment producing bending at support
 I = Moment of inertia of complete cable and damper at support
 I_s = Moment of inertia of steel-core of conductor
 I_a = Moment of inertia of aluminum part of conductor
 I_d = Moment of inertia of damper at support
 M = Virtual modulus of elasticity of complete conductor and damper
 M_s = Modulus of elasticity of steel
 M_a = Modulus of elasticity of aluminum
 M_d = Modulus of elasticity of damper material

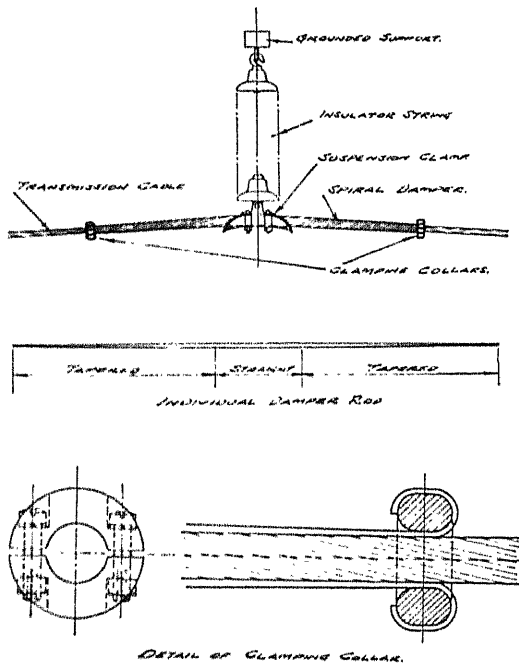


FIG. 4

$$V = \sqrt{\frac{P_o}{W}} = 2 L F \quad (1)$$

$$y = \frac{A}{2} \sin \theta = \frac{A}{2} \sin \frac{\pi x}{L} \quad (2)$$

$$\tan Q = \frac{dy}{dx} = \frac{\pi A}{2 L} \cos \frac{\pi x}{L} \quad (3)$$

$$= \frac{\pi A}{2 L} \text{ at origin when } x = 0$$

$$dl = \left[1 + \left(\frac{dy}{dx} \right)^2 \right]^{\frac{1}{2}} dx \quad (4)$$

$$\begin{aligned} \left(\frac{dy}{dx} \right)^2 &= \frac{\pi^2 a^2}{L^2} \cos^2 \frac{\pi x}{L} \\ &= \frac{\pi^2 a^2}{L^2} \left(1 - \sin^2 \frac{\pi x}{L} \right) \text{ when } a = \frac{A}{2} \end{aligned}$$

$$dl = \sqrt{\frac{L^2 + \pi^2 a^2}{L^2} - \frac{\pi^2 a^2}{L^2} \sin^2 \frac{\pi x}{L}} dx$$

$$\frac{\pi x}{L} = \theta, \quad x = \frac{L \theta}{\pi}, \quad dx = \frac{L}{\pi} d\theta$$

$$dl = \frac{L}{\pi} \sqrt{\frac{L^2 + \pi^2 a^2}{L^2} - \frac{\pi^2 a^2}{L^2} \sin^2 \theta} d\theta$$

$$= \frac{\sqrt{L^2 + \pi^2 a^2}}{\pi} \sqrt{1 - \frac{\pi^2 a^2}{L^2 + \pi^2 a^2} \sin^2 \theta} d\theta$$

$$l = \frac{2 \sqrt{L^2 + \pi^2 a^2}}{\pi} \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{\pi^2 a^2}{L^2 + \pi^2 a^2} \sin^2 \theta} d\theta$$

This expression can be integrated approximately as follows:—

$$l = L \sqrt{1 + \frac{\pi^2 a^2}{L^2}} \left[1 - \frac{1}{4} \frac{\pi^2 a^2}{L^2} \left(1 + \frac{\pi^2 a^2}{L^2} \right) \right]$$

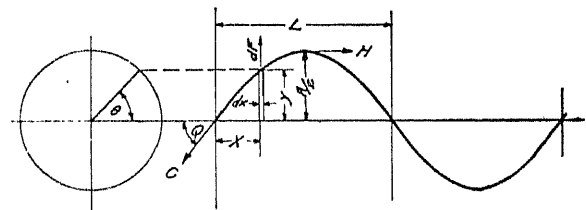


FIG. 5

$$\begin{aligned} & - \frac{3}{64} \frac{\pi^4 a^4}{L^4 \left(1 + \frac{\pi^2 a^2}{L^2} \right)^2} \\ & - \frac{5}{256} \frac{\pi^6 a^6}{L^6 \left(1 + \frac{\pi^2 a^2}{L^2} \right)^3} \end{aligned}$$

put

$$m = \frac{\pi^2 a^2}{L^2} \text{ and } \sqrt{1+m} = 1 + \frac{1}{2} m - \frac{1}{8} m^2 + \frac{1}{64} m^3;$$

consolidating:

$$l = L \left(1 + \frac{1}{4} m - \frac{3}{64} m^2 + \frac{5}{256} m^3 \right)$$

$$l = L \left(1 + \frac{1}{4} \tan^2 Q - \frac{3}{64} \tan^4 Q + \frac{5}{256} \tan^6 Q \right) \quad (5)$$

Since for any case of vibration recorded Q is very small (not over approximately $\frac{1}{2}$ deg.) $\tan Q$ is small and l is so little greater than L that the tension P may be taken constant. This is the fundamental assumption upon which equation (1) is based.

$$\begin{aligned}
 R &= \frac{\left[1 + \left(\frac{dy}{dx} \right)^2 \right]^{3/2}}{\frac{d^2 y}{dx^2}} \\
 &= \frac{\left[1 + \left(\frac{\pi A}{2L} \cos \frac{\pi x}{L} \right)^2 \right]^{3/2}}{\frac{\pi^2 A}{2L^2} \left(-\sin \frac{\pi x}{2} \right)} \quad (6) \\
 &= \frac{2L^2}{\pi^2 A} = \left(\frac{1}{\tan Q} \right) \left(\frac{L}{\pi} \right) \text{ when } x = \frac{L}{2} \quad (7)
 \end{aligned}$$

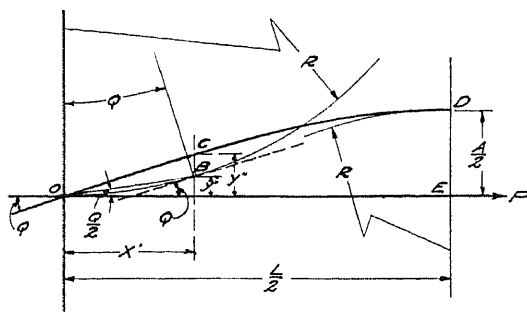


FIG. 6

When the loop is vibrating freely in the span, away from a support, no bending occurs at O and the angle Q is produced by the balanced motion of the adjoining loops. If a support occurs at O , the angle Q becomes zero at the left of O and the conductor is alternately bent up and down through the angle Q . Although the angle Q is small, the bending produces very considerable fiber stresses which added to the direct tension in the cable has produced breakage.

In Fig. 6, a circle of radius R is drawn tangent to the axis of X at the origin O . At a point B a tangent is drawn to this circle parallel to OC . This tangent makes an angle Q with the axis of X . The arc OB subtends an angle at the center equal to Q and the angle

$$BOE \text{ equals } \frac{Q}{2}.$$

The arc length OB is obtained as follows:

$$\text{Arc } OB = \frac{Q}{360} 2\pi R$$

Chord $OB = \text{arc } OB$, very nearly, since Q is small.

$$y' = OB \sin \frac{Q}{2} \quad (8)$$

Since Q is small X may be taken equal to OB and substituting this value of X in equation (2):

$$y'' = \frac{a}{2} \sin \frac{\pi X'}{L} \quad (9)$$

When the loop is freely vibrating the tension in the wire produces no bending at O . When bending occurs

at O the resultant of the tension in the cable does not pass through O and the bending moment is the product of the tension and the offset of the bend.

Under the conditions indicated in the figure the bending moment at O is represented as follows:

$$K = P \cdot BC = P (Y'' - Y'), \text{ very nearly.} \quad (10)$$

In order to satisfy these conditions the following relation must obtain:

$$IM = RK \quad (11)$$

In order to satisfy this condition, I must usually be greater than the value corresponding to the wire itself. This value may be obtained by a reinforcing wrapping or damper, the proportions of which may be determined from the following expression.

$$RK = IM = I_s M_s + I_a M_a + I_d M_d \quad (12)$$

These relations are apparent from Fig. 7, remembering that the deflections for the several parts of the conductor and damper are the same for the same lever arm h .

If R' represents the radius of the curve at the right of O before any damper is applied, it is apparent from equation (10) and the discussion immediately preceding it that there is a corresponding value of K . By assuming a series of values of R and determining the corresponding values of K the proper value of R' is obtained when the resistance to bending of the conductor, without damper, equals the bending moment thus produced. Equation (12) may be written as follows to illustrate this balanced condition:

$$R' K' = I_s M_s + I_a M_a \quad (13)$$

The moment of inertia of a bundle of wires is equal to the sum of the moments of the individual wires about their respective neutral axes. If the wires are all under tension and parallel the moment of inertia of the bundle may be taken as the sum of the moments of the individual wires about the neutral axis of the bundle.

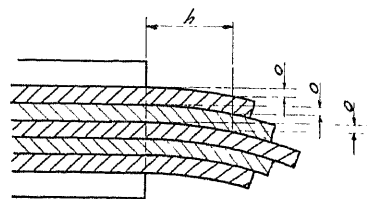


FIG. 7

In a conductor the wires are usually arranged in a spiral, which tends to equalize the stresses due to bending. On the other hand friction between the wires tends to counteract this effect.

Referring to Fig. 8 and first assuming the case at the middle of a loop, the individual strands are only restrained from slipping lengthwise with respect to one another by the friction between them produced by the conductor tension. Examining the behavior of an

individual strand in the outside layer and denoting tension stress by the sign (+) and compression stresses by the sign (-), the part of the strand outside of the neutral axis of the complete conductor is (+) and the part inside is (-). At the crossing of the neutral axis the stress due to bending is zero. The small arrows indicate the direction in which the material of the strand tends to flow under the action of these stresses.

The adjacent strands of the same layer are moving almost synchronously with respect to each other. This is not the case, however, between the strands of adjacent layers and particularly where they cross each other at the neutral axis. In Fig. 8 the arrows indicate that while the outer strand tends to move toward the left the inner strand is trying to move toward the right.

If the strands of the successive layers were spiralled in the same direction much of this tendency would be removed. Steel cables designed to travel over sheaves are usually made this way and in a few cases of long

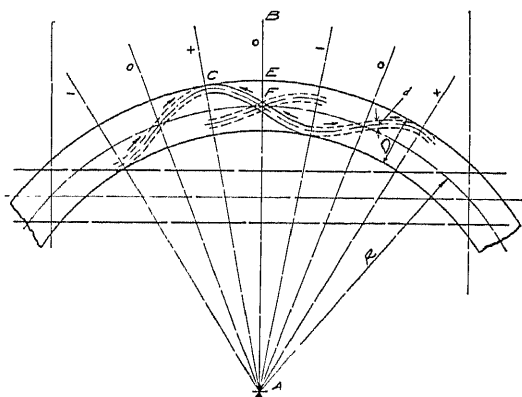


FIG. 8

river crossings the steel cores of A. C. S. R. have been so specified. However, the reversed lay construction is almost universally used for transmission conductors and so far as the writer is aware no conductor failure has been identified with this cause.

If the strands are not restrained by friction, the fiber stress in each strand is due only to bending about its own neutral axis. Thus:

$$J_{Md} = \text{Max. Fiber Stress} = M_a \frac{d}{2R} \quad (14)$$

If the friction between the strands were increased by any means so that all relative slipping ceased, then the maximum fiber stress would be expressed as follows:

$$J_{MD} = \text{Max. Fiber Stress} = M_a \frac{D}{2R} \quad (15)$$

The true value of the fiber stress is somewhere between these extremes and is close to that given by equation (14).

Suppose now that a supporting clamp is applied to

the conductor in such manner that all of the strands to the right of the line AB , Fig. 8, are prevented from slipping. The flow in the strand shown in Fig. 8 will no longer be equalized at C and a longitudinal stress approaching the value given by equation (15) will result. The strand which crosses line AB at E will not thus be affected and its stress will be represented by equation (14). Other strands have intermediate values of stress.

Referring to equation (13) the values of I_s and I_a will depend upon whether the neutral axis is taken at the center of the conductor or at the center of each strand. Similarly, the value of R' will depend upon this same condition. The rather interesting fact develops that the fiber stress in the undamped conductor at the support is practically the same no matter which of these assumptions is made.

Table III represents one of the sets of observations given in Table I. The column headed J_d' represents the fiber stress in the conductor at a support with neutral axis at center of each strand. J_D' is the corresponding value with axis at center of conductor. Throughout this list these values are practically equal.

Table III further illustrates the effect of a damper cage consisting of seven aluminum rods each 0.475 inch diameter. In this case the radius of curvature is represented by R_d'' , the fiber stress in the aluminum part of the conductor is given by J_d'' and the stress in the damper rods by J_d''' .

In this case the bending moments and stresses are based on the assumption that the neutral axis is at the center of the individual members of the entire conductor and damper.

In Table III the last two cases are hypothetical as regards loop length and amplitude for -20° fahr. All the others are observed.

In the following nomenclature the subscripts 0, 1, 2, 3, 4, 5, 6 refer respectively to the central wire and the successive layers of the conductor and damper from the center outward. The small letters i_0, i_1 , etc., refer to the moments of inertia of the individual wires of the several layers. The large letters I_0, I_1 , etc., refer to the moments of inertia of corresponding layers. The small letters n_1, n_2 , etc., refer to the number of wires in each layer. The small letters d_0, d_1, d_2 , etc., are the diameters of individual wires of the respective layers. The letters M_0, M_1 , etc., refer to the respective moduli of elasticity of the materials forming the respective layers. D_0, D_1, D_2 , etc., refer to the diameters of the circles circumscribing the respective layers.

Referring to Fig. 9:

$$d_0 = D_0$$

$$d_1 = D_0 \left(\frac{\sin \theta_1}{1 - \sin \theta_1} \right) \text{ when } \theta_1 = \frac{360}{2 n_1}$$

TABLE III

Conductor—266800 c. m. A. C. S. R. Stranding—6 x .2108" Alum. 7 x .0705" Steel							Diameter .633" Wt. Per Ft. .343" E .2362 H _a .885 H _s .115		(I _a M _a + I _s M _s) d = 5480 (I _a M _a + I _s M _s) D = 49160 (I _a M _a + I _s M _s + I _d M _d) d = 162900—With 7 x .475" alum. damper						
Span (ft.)	Temp. (fah.)	P (lbs.)	L (ft.)	A (1/32")	F (C. P. S.)	Tan Q	R (ft.)	J M _d (lbs./D")	R _d ' (ft.)	J _d ' (lbs./D")	RJ' (ft.)	J _d ' (lbs./D')	R _d ' (ft.)	J _d ' (lbs./D')	J _d ' (lbs./D')
1020	54	2260	4.0	4.	30.0	.004090	311	254	46	1725	139	1710	288	274	619
1020	58	1825	9.5	4.	22.3	.001723	1754	45	122	650	361	658	658	120	271
1020	70	1710	12.0	6.	17.2	.002045	1867	42	103	768	315	754	572	138	312
1020	70	1710	14.0	10.	12.2	.002921	1525	52	70	1130	212	1120	413	192	441
1020	70	1710	4.0	2.	45.0	.002045	622	127	106	747	327	721	766	103	233
920	18	2370	20.0	6.	13.6	.001228	5183	15	146	542	442	548	800	99	223
920	28	2270	8.8	4.	26.0	.001859	1507	52	103	772	296	802	550	144	324
920	37	2135	10.0	6.	22.0	.002454	1296	61	78	1015	231	1028	433	182	412
920	42	2005	4.2	1.	52.0	.000974	1372	58	195	405	629	377	1283	62	139
920	48	1850	6.0	5.	35.0	.003410	560	141	58	1355	179	1325	334	237	535
920	59	1840	8.5	3.	28.0	.001444	1873	42	145	547	425	559	775	102	230
1020	-20	2720	4.0	4.	30.0	.004090	311	254	41	1935	128	1850	250	316	714
1020	-20	2720	14.0	10.	12.2	.002921	1525	52	56	1416	173	1370	313	253	570

$$d_2 = D_1 \left(\frac{\sin \theta_2}{1 - \sin \theta_2} \right) \text{ when } \theta_2 = \frac{360}{2 n_2}$$

$$d_6 = D_5 \left(\frac{\sin \theta_6}{1 - \sin \theta_6} \right) \text{ when } \theta_6 = \frac{360}{2 n_6}$$

$$I_0 = i_0 = \frac{\pi}{64} d_0^4$$

Assuming the neutral axes at the center of each strand:

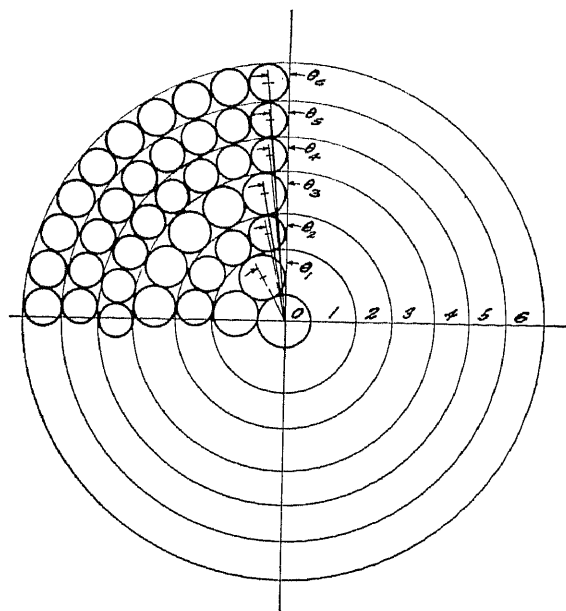


FIG. 9

$$I_1 = \frac{n_1 \pi d_1^4}{64}$$

$$I_2 = \frac{n_2 \pi d_2^4}{64}$$

$$I_c = \text{Total moment of inertia} = I_1 + I_2 \text{ etc.}$$

Assuming the neutral axis at the center of the cable:

$$I_1 = \frac{\pi}{64} n_1 d_1^4 + \frac{\pi}{16} d_1^2 (D_0 + d_1)^2 [R^4 \cos^2 \theta_1 + \cos^2 3 \theta_1 + \dots + \cos^2 (2 n_1 - 1) \theta_1]$$

Equation (14) is based upon the first assumption and equation (15) upon the second.

To illustrate the application of this analysis the values in the following table have been worked out for the several cases in Table I for which the values in columns 11 to 19 inclusive are given. In these cases a single layer of 12 iron wires has been assumed. The values of I_d should be compared with those in column 19. Any considerable discrepancy between these values can be corrected by assuming a different number of wires for the damper. Also considerable variation is possible when different materials for the damper wires are used.

Diam. of cylindrical part of damper wires. (In.)	Values of I_d
0.4153	0.578,253
0.3643	0.342,379
0.3333	0.239,959
0.3013	0.160,253
0.2413	0.065,928

Equation (15) was used in the above analysis.

The effect of the damper is not only to increase the radius of the bend at the support but also to reduce the amplitude, frequency, and loop length which still further reduces the fiber stress due to bending.

It may be added that dampers similar to the type described herein have been in operation in certain cases for about three years, without breakage of conductor strands, whereas before the application of the dampers, breakages had occurred within from two to three months after installation.

In conclusion, the fact remains that in none of the cases recorded herein does the total normal tension stress plus the bending stress in the aluminum part of

the conductor reach the endurance limit values which have as yet been established by the usual laboratory methods. The inference is that the bending action at the support creates an unequal distribution of the stresses between the several strands alternately overloading some of them and relieving others. If this bending can be sufficiently restricted, the damaging results must disappear.

The problem has been approached in a different manner by Mr. G. H. Stockbridge, Engineer of Transmission, Southern California Edison Co. He has successfully suppressed vibrations by means of an ingenious device located in the span some distance from the support.

The writer is indebted for valuable assistance to Prof. William R. Work, and Mr. F. E. J. Litot, Carnegie Institute of Technology. Also to Messrs. L. W. Henry, M. E. Noyes, H. H. Rodee, L. H. Hemeter, L. D. Hutcheson, R. L. Templin, and G. W. Stickley, Aluminum Company of America.

Discussion

D. D. Clarke: Mr. Varney's paper has been of very great interest to me, because he depicts a problem with which I have come in contact.

One item of vibration that he mentioned deserves more attention. When the span is divided into several of these vibration loops, the loops seem to travel from one end of the span to the other and back again. In these cases, such rough and crude measurements as we have made indicate that there was a change in the tension, longitudinally, of the wire. This would not amount to a great percentage of the stress in the conductor.

This is the first item of research that I have noted that covers a definite procedure with regard to quantities involved, and leads directly to solving the reason for certain things happening in conductors, that we know do happen. Here is a very definite field for providing the proper devices to eliminate breakage troubles, due to the fatigue of conductors, even the fatigue of supports of the conductors.

In our experience with several thousand miles of this sort of wire in service, the breakage of the conductors at the point of support has been nil, but the breakages of supports have indicated the necessity of getting into the problem, and I have a very optimistic outlook, because of this research as demonstrated in the paper.

J. B. MacNeill: Considerable work has been done, the last two or three years, in connection with the measuring of stresses in railroad tracks, by actual recording devices of a sensitive nature. I was wondering if anything similar had been done here, or if an adaptation of those devices would eliminate some of the assumption it has been necessary to make. Personally, while I do not know much in detail about these devices, I think there would be considerable hope of help in that direction.

Eli Ettlinger: There is one particular phenomenon mentioned by Mr. Clark, that I think is of significant interest, and that is the question of the appearance of travel of the wave along the conductor. To me, that indicates directly the fundamental phenomenon which is taking place in the vibration of the conductor, which perhaps has been something of a mystery and still, perhaps, is fundamental.

The setting up of a steady state of vibration can fundamentally be broken down mathematically, and physically can be so demonstrated, into two decaying traveling waves in opposite directions. The original train of traveling waves in one direc-

tion and the reflected waves from the distant end, when superimposed, develop these standing waves.

Perhaps with the wind acting on the various portions of the suspended wire, the fundamental traveling wave is not of the same length as the reflected wave, and therefore the standing wave has the appearance of moving along.

When we undertake to analyze this vibration problem, I think it is well to get to the fundamental physical conception of the problem, before we attempt to tackle the mathematical analysis of it. Mr. Varney's first paper, some years ago, gave something of the conception of those fundamentals, attempting to set forth the manner in which these vibrations are set up by the wind. So far, we know of no other particular reason for the appearance of these vibrations. If we analyze these vibrations in terms of the traveling wave related to the fundamental velocity which a traveling wave may have, due to the tension and mass of the wire, as shown in Mr. Varney's first paper, then perhaps from that we can begin to get an analysis of what is occurring on a rigid support. However, when we get to a semi-flexible support and then perhaps to the flexible support, we have no definite manner of analyzing the problem.

As I understand it, Mr. Varney has made his mathematical attempt here on the assumption that the support is rigid, which is not directly true on our ordinary suspensions on transmission conductors. I have in mind, directly in connection with the analysis on the rigid support, a very recent opportunity to observe the breakage of wires. It happens to be a case to which most transmission men have neglected to give their attention in the past, and that is to overhead ground wires.

I speak specifically of a ground wire of high-strength steel, rigidly attached to wood poles. I have three samples of the broken wire. The attachment was perfectly rigid, there was no chance of flexibility, and the indications of vibration were quite obvious. The breaks occurred directly under the rigid support. The breaks were characteristic in that case, as Mr. Varney said, as being clean-cut and not drawn as if tension were the cause of the trouble.

I think that perhaps the radius, as indicated for bends which may take place at the rigid support, is a very important item. We have development by Mr. Varney now, which gives us some idea of the importance of that item, and a means of determining its magnitude.

In the cases of breakage mentioned the repair was made by attaching a parallel piece of cable with Crosby clips, which at the same time furnished the additional mass along the wire, accomplishing the same thing Mr. Varney indicates.

The fundamental thought, given in many texts, of the traveling waves as taking place on ordinary wires and the like, may well be kept in mind in attacking the vibration problem.

The tension and the particular materials that are used in conductors requiring certain tensions to give certain sags, develop certain span lengths, would seem to be of vital importance. I mention specifically that the particular ground wire which was in trouble was of high-strength steel. The thought occurred to me that, perhaps, if the ordinary Siemens-Martin steel had been used in its place, our difficulties might not have been as pronounced.

The relationship of tension to mass is a direct function of the velocity of propagation of the traveling wave on a wire supported by rigid supports or otherwise. It is my thought that where that velocity of propagation is greatest, where the tension is highest, perhaps the bending is sharpest at a rigid support. It indicates something with relationship to the steepness of the wave front of the traveling wave; that steepness of wave front brings to mind the kind of radius which will develop at the support. I am inclined to reduce tensions where possible on conductors, in order to hold down that particular factor, which I term the velocity of propagation.

The stringing tension of that ground wire, using high-strength

steel under maximum loading conditions, would have been of the order of 5000 lb.; using a $\frac{3}{8}$ -in. Siemens-Martin would have given satisfactory clearance in the same case, and would have held our tension down to 3000 lb. The relationship of velocity of propagation would have been reduced by the square root of those tensions.

In closing I would suggest to Mr. Varney that, perhaps, the fundamentals with relationship to the traveling wave, which must first be set up in order to get these standing waves, is probably of as vital importance in the study of this problem as the pure phenomena of the standing wave.

Theodore Varney: Replying first to Mr. MacNeill's question, I understand him to ask whether we have tried to carry on any accurate laboratory experiments whereby we measure the movements and stresses set up in the individual strands of the cable.

We must admit that our experimental work has lacked refinement. At the Carnegie Institute of Technology in Pittsburgh where we have been experimenting for the last year with the wooden frame and cable, we have not yet been able to work out any very accurate method of recording these experiments. As far as I can see, it will be difficult to obtain such records. We have tried to detect with a high-power microscope the actual movement of the particles of the cable but we could do this only in the outside strands.

The idea we had was, I think, similar to what Mr. Ettlinger suggests, *viz.*, the rather high velocity of a vibration or standing wave in a cable at pretty high tension conveys the thought of impact. That is what we tried to check with the microscope, but when we found we could not observe any longitudinal motion in the strands at the side of the cable, we came to the approximate conclusion that the stress effect was confined to bending.

Mr. N. B. Obbard, of the American Bridge Company, at Pittsburgh, once suggested to me the theory that the resulting wave in the conductor might be due to the combined effect of torsional, longitudinal, and transverse vibration.

The transverse wave predominates, but there is of course a very slight longitudinal varying stress which must set up a wave some 10 or 12 times higher in velocity than the transverse wave. There must also be present a slight amount of torsional vibration due to the spiral effect of the strands.

The point Mr. Obbard made was that if the period of the natural torsional vibration coincides with the eddy frequency of the wind, the transverse vibration would be amplified on the same principle as that used by Floettner in the rotating masts of his ship.

Since the longitudinal vibration might also have the effect of setting up transverse vibration, if of a proper frequency, Mr. Obbard thought all three might combine in some proper phase relation to account in some measure for the large amplitudes recorded in certain cases.

The speaker has no data to substantiate this theory and is rather of the opinion that the large amplitudes are explained by resonant conditions of the conductor with its system of supports together with a steady wind velocity acting uniformly over a considerable length of line.

I should like to add that this paper is not an attempt to go into deep mathematics. Mathematics have been introduced simply in the effort to explain observed effects. The theory of the radius of bending affords a simple explanation of what goes on in a conductor when it vibrates and further affords a simple remedy.

It is true if you add stiffness you will reduce the amplitude. Just how much is difficult to say without actual experiment, but just in proportion as the amplitude is reduced the vibration will be "damped." In other words, the damper scheme reduces the stresses to a safe point even if the amplitude were not reduced, but in addition to this if it reduces the amplitude we are still further on the side of safety.

It is true that the theory developed in this paper is based on the assumption of a rigid support which is not actually the case in any transmission line. It is believed, however, that whatever flexibility is provided by a well designed pivoted suspension clamp or other means is in the direction of additional safety. All that the writer has said as far as he can see, applies just as well under such conditions with probably improved results.

As to the question of tension in the cable, it is true that if tension is reduced the bending moment is reduced, provided the amplitude remains the same. Very often, however, when a cable is strung slack, "whipping" results. Whipping, as the speaker understands the term, is merely a low-frequency vibration of large amplitude. Such a vibration has been known to have very destructive effects. The type of damper described in this paper will tend to limit whipping.

The point is, if it is not necessary to string the conductor tight, don't do it; but if there is an economy to be gained, do not hesitate to do so. In either event, suitable safeguards against vibration or whipping should receive consideration in the construction of any transmission line.

The Planning of Telephone Exchange Plants

BY W. B. STEPHENSON¹

Non-member

Synopsis.—This paper discusses procedures followed in planning future extensions to telephone exchange plants to care for increased demand for telephone service. An outline is given of the methods employed in forecasting future demand for telephone service and in determining the most efficient design of the plant to meet the service requirements. The uses made of engineering comparisons in solving the economic phases of various kinds of telephone engi-

neering problems are discussed, with particular reference to location and size or extent of major items of plant as well as the time when they should be ready to give service. Emphasis is placed upon the importance of those factors less readily evaluated, such as service factors, practicability from a construction and operating standpoint, flexibility, etc.

* * * * *

TELEPHONE engineering involves many widely varying problems. Among these is the design of the various component parts of the telephone plant. This includes the design of central office buildings, the design of switching and power equipment to be housed in these buildings, the design of the trunk cable system with any loading necessary in order to connect these buildings, and the design of the distribution system. The distribution system includes, of course, the conduit, pole lines, feeder cable, distributing cable, house cable, etc., necessary to reach the subscriber's premises and connect his station equipment with the switching equipment in the central office.

Before the building can be designed in detail, however, determinations must be made as to whether the building should be built at all, where the building should be located, when it should be ready for occupancy, what area will be served by the building, and how much equipment must ultimately be housed in the building. Before the equipment for any particular building can be designed, we must know what type of equipment should be used and about how much business will be handled on this equipment. Before the trunk plant can be properly designed, we must know our future plans for increasing or decreasing the operating centers in a city, how much business will be handled on this trunk plant, and the economic allocation between transmission loss in the trunk plant and the transmission loss in the distribution plant. Before the distribution plant can be designed, we must know our future plans for serving the area involved. In other words, it is evident that a large amount of broad preliminary planning must be done before the detailed design of a telephone exchange plant can be undertaken.

It is the purpose of this paper to give a general idea of the methods now in use in this preliminary planning. The discussion will be confined to the exchange plant problem for the larger towns and will not go into the toll plant problem. To avoid confusion a "telephone exchange plant" will be defined as that plant serving a single community, for example, the "St. Louis

exchange," or the "Kansas City exchange." An "operating center" will be defined as that part of the exchange plant housed in one building. There are thus several operating centers in a large exchange.

The first step in attacking the telephone planning problem for a city, is to make a determination as to about how much business will be cared for. This problem is attacked on very broad and thorough lines. An attempt is made to arrive at the estimated population of the city in question for some 18 or 20 years hence and also for intermediate periods of about 6 and 12 years. From these estimated future populations and other careful studies, which will be touched upon briefly later, an estimate is made as to the number of telephone stations and lines which will be in service 6, 12, and 20 years in the future. Moreover, this survey shows the location of these lines and stations.

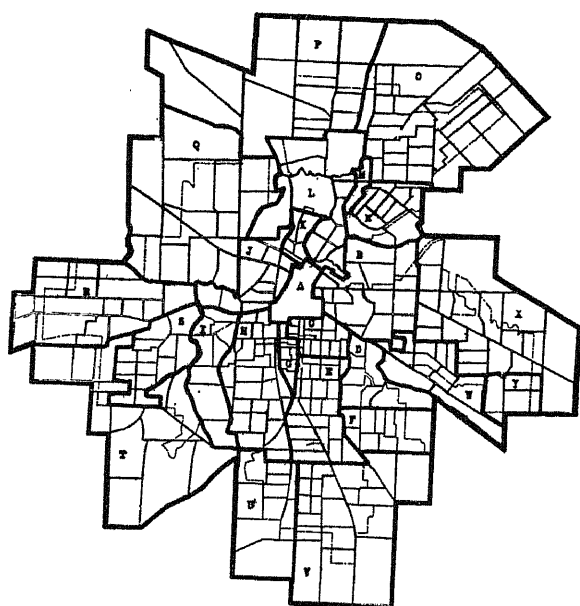
It has been found that the various parts of a city have wide differences in market conditions or, in other words, the possibilities of selling telephone service. One of the first steps in making a survey is to divide the town up into so-called market areas or areas which display somewhat the same economic characteristics. These market areas are further broken down for convenience sake into what is known as "house-count sections."

The accompanying map (Fig. 1) indicates for an assumed case how a city is divided into market areas and house count sections for purposes of a survey. Market area "A," for example, would consist of the downtown business section which includes all the office buildings, department stores, hotels, and large retail firms together with some warehouses and manufacturing plants along the two railroad lines. Market area "H," for example, might be a residence area with the medium classes predominating, while market area "D" would consist of the highest type of residence district, including very little neighborhood business.

After the above divisions in the area of a city have been made, a card record is made of all the existing subscribers. These cards show the name, the telephone number, and the address of each subscriber. These data are then summarized on field survey sheets which are made up by blocks. The field men then

1. Southwestern Bell Telephone Company, St. Louis, Mo.
Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.

take these sheets and go out into the field, visit the block covered by each sheet and for the business subscribers indicate the class of business, and for the residence subscribers the type of residence, and the estimated rental classification, that is, the estimated amount of rent that the subscriber is paying. The rental classification is merely a convenient means of arriving at some kind of an idea of the economic status of the family. It has been found that the market for telephone service is better among those subscribers who



Market Areas and
House-Count Sections

FIG. 1

are better able to pay for this service and that there is rather a direct relation between the rental classification and the market for service in any one market area. This will be different for the various market areas, however. For example, a \$40 rental in a market area inhabited by university people will represent a better market for telephone service than a \$40 rental in an area inhabited by steel workers.

These field sheets are later summarized so that we can tell about what percentage of the residence subscribers of the various classifications in the various market areas take telephone service and what class of service they take, that is, individual lines or party lines. These summaries also indicate the amount of neighborhood business and the amount of downtown business. The completion of the surveys then has given us very detailed information on the present market conditions for telephone service in the city in question.

In making an estimate for the future, the first and possibly one of the most difficult tasks is to arrive at an estimated population of the city for some 15 to 20 years hence. This problem is attacked on broad lines. Periodic estimates are made of the population of the

United States, taking into account emigration, immigration, and the excess births over deaths. Similarly the estimated population of the United States is broken down by states and later distributed to the cities and other communities. This gives us the best possible estimate of the future population of the city in question. This estimate takes into account, not only local conditions, such as the trend of manufacturing, railroad facilities, etc., but also the national trend. These estimates of population are made in an impartial manner. Population estimates made by city boosters are inclined to be tinged with the hopes of the individual estimator, but every effort is taken to eliminate this factor from the estimates made for telephone purposes.

Data are at hand showing the average size of the families of the city in question and also the trend as to the increase or decrease in size of families. From the estimated future population, and estimated persons per family, the estimated number of families is obtained. Based upon the intimate knowledge of the city which was obtained in the survey, an estimate is made

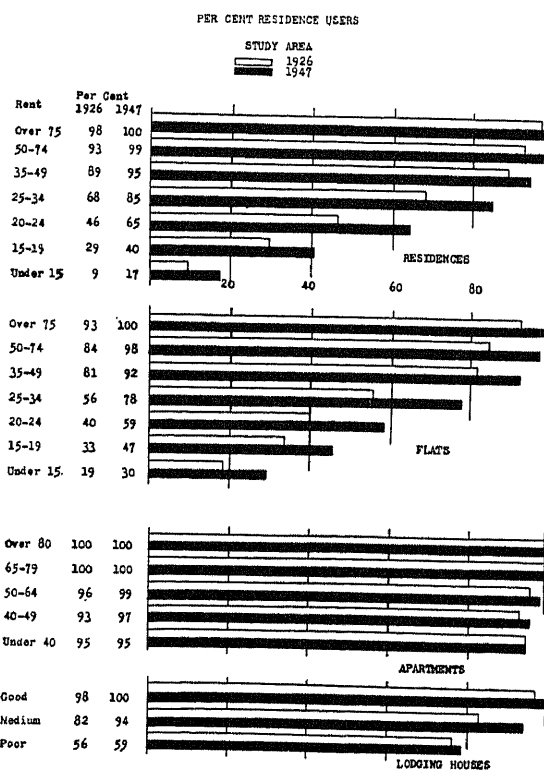


FIG. 2

as to the number of families which will live in the various house-count sections in the city. Based upon the knowledge of the business in the town obtained from the survey and the relations which exist between business firms and residence population, an estimate of the future downtown and neighborhood business firms is obtained. From these residence and business data, an estimate of the future market for telephone service in the city is arrived at.

It is thought that the accompanying Fig. 2 showing a typical per cent residence users will be interesting. It will be noted that the percentage of users in the various rental classifications is different for different kinds of dwellings, that is, residences, flats and apartments, and lodging houses.

A large map of the city is prepared and the estimated number of telephone lines for the future period is placed in each city block, which gives the best possible data for the planning of the telephone plant. The accompanying map (Fig. 3) is a spot map showing

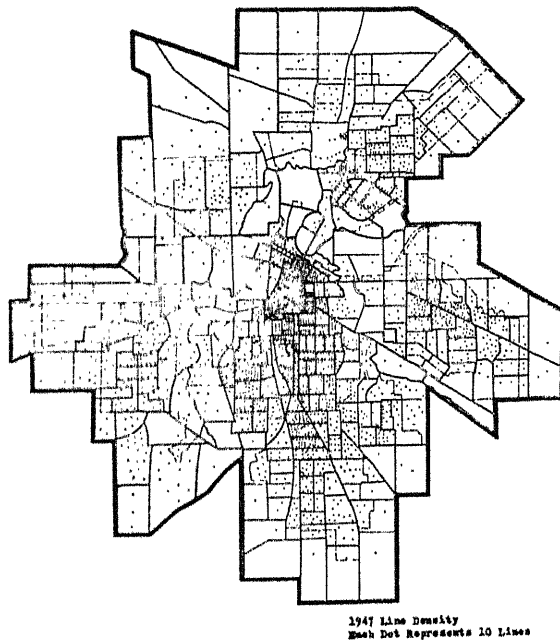


FIG. 3

one spot for each ten telephone lines. The map has been prepared in spot map form since this will give a better idea of the telephone density than a map showing the number of lines in each block. The map showing numbers of lines is used in the actual calculations, of course, instead of the spot map.

The next problem is to determine the number of operating centers which will be required to serve the city and the best location for these operating centers. It would probably be physically possible to serve some of our larger cities from one operating center. This would involve an enormous equipment building at some central location and it would be necessary to provide cables connecting all the subscribers in the city to the one building. It is apparent that the average length of the subscribers' lines in this case would have to be very high. In order for the subscribers farthest from the operating center to be able to talk, it would be necessary to use wire of very large comparative diameters or take some other expensive means for eliminating undue transmission loss. In a city of perhaps 100,000 population, it might be necessary to consider seriously a single center plan, but it is obvious that in the case of

the larger cities such an arrangement would be out of the question.

It would also be possible to go to the opposite extreme and place a little operating center in each block in the city. In this case, the length of the subscribers' lines would be very short, being all less than one block long. All of these little centers, however, would have to be connected by trunks making a tremendously expensive trunk plant. Arrangements would have to be made to provide switching and transmission power at each one of these little centers and the cost of all of these little buildings would probably be much greater than the cost of fewer but larger buildings. This arrangement is obviously impossible from an economic standpoint and impracticable from a physical standpoint, and the correct answer is some place between the one center and many center plans.

The method followed in solving these problems, will be illustrated by assuming a sample problem and carrying through the line of reasoning. The sample problem is rather a simple problem for a small city, but exactly the same principles are involved as in the

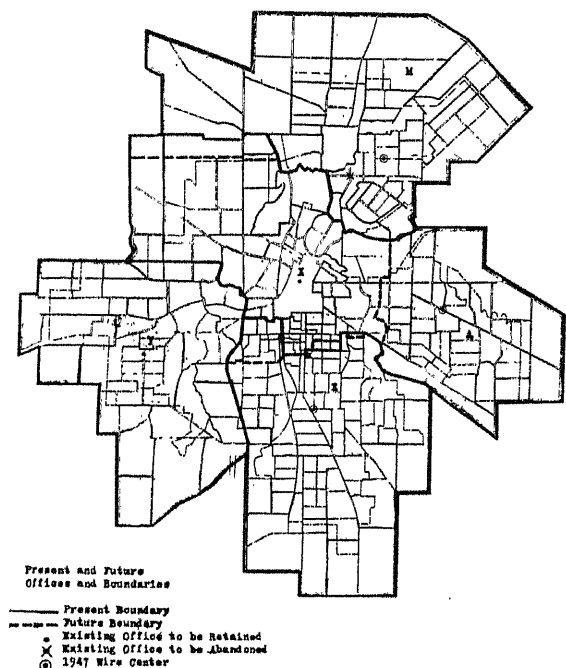


FIG. 4

larger towns, such as St. Louis. This is the type of problem which is met today in most of our cities.

The accompanying map (Fig. 4) indicates for our assumed problem the present centers, the present boundaries between the centers, and the future centers with the future boundaries which are determined by our studies.

Let us assume that the downtown "X" center has new dial type equipment housed in a new building. Very careful studies were made before this building was built, of course. A large investment is involved in this building and equipment which were designed so that

they can be extended to last for many years. It is a safe assumption, therefore, that this building will be retained at its present location. Let us also assume that the "Y" operating center has just been built as a result of careful studies and is also designed to last for many years. On account of the large investment involved here, it is a safe assumption that this building will also be retained at its present location.

The "Z" building is several years old and houses

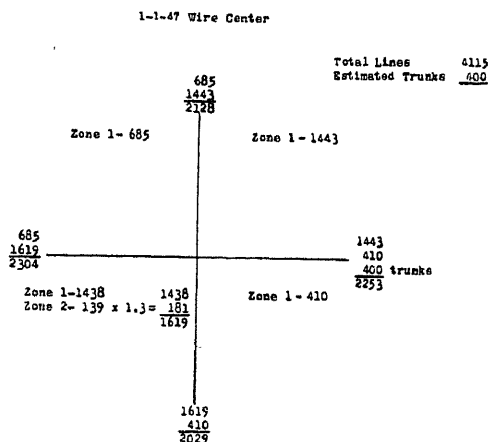


FIG. 5

manual equipment. On account of the large number of lines in this part of the town, we know from past experience that there is no question but that an operating center must be located some place in this part of town. We proceed, therefore, to determine what the future wire center will be.

Let us assume that the "M" center has manual equipment located in less permanent quarters. There are not so many lines in this part of the city as in the "Z" section and there might be some question as to whether there should be an operating center located in this part of town or whether this area should be served from the downtown building. We proceed, therefore, to determine this by methods which will be outlined later on.

An inspection of the map indicates that the "A" section is rather isolated from the rest of the town and presents somewhat the same problem as the "M" area, except that the "A" area is somewhat smaller and is now served from the downtown building. There is some question as to whether there should be a center in this part of town and we proceed with a solution of this problem together with a determination of the proper wire center.

In the above paragraphs, the term "wire center" has been mentioned several times. A wire center may be defined as that location for an operating center at which the cost for subscribers' lines and trunks will be a minimum. The determination of a wire center is a cut-and-try-problem which can be illustrated by the accompanying Fig. 5, illustrating the wire center for the "A" area.

From an inspection of the "A" area, a trial center is selected and axes are drawn on the map through this center following the direction of the principal streets. The lines in each quadrant are then equated in terms of the cost of the finest gage of conductor contemplated and summarized. The inter-office trunks are also included in this calculation. If it is found after these lines are counted that the sum of the equated lines in the various quadrants does not balance, a new center is tried to determine a better balance. When a balance is obtained, this point will be a wire center.

It is necessary to assume a boundary between the center in question and the adjacent centers for each trial wire center. This boundary is assumed to be equidistant from the operating centers, that is, each station is served from the nearest operating center.

After the wire center is calculated by these methods, practical checks are applied to be sure that the proper center is selected, taking into account local conditions as to topography and street layout.

In order to determine the best arrangement of operating centers, various trial arrangements are assumed, and certain costs involved in serving the city at the 20 year period (in this case 1947) in the future are calculated. All these costs are reduced to an annual charge basis. Fig. 6 indicates the various plans tried in our problem. With the exception of the locations of the "X" center and the "Y" center which were outlined above, the problem is solved assuming that an ideal condition will exist. The engineer assumes that he can build an ideal plant to handle the 1947 development and

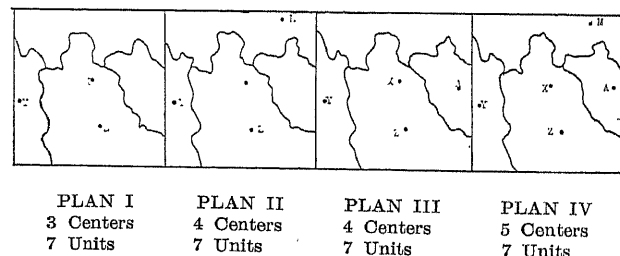


FIG. 6—1947 COMPARISON

The above arrangements are compared as regards annual charges for each of the following items:

- Subscribers' lines
- Trunks
- Central office equipment
- Maintenance labor
- Land

he has not taken into account any losses which might be occasioned due to the fact that the present plant would not fit in well with the ideal 1947 plant. The method of caring for the effect of the present plant will be outlined later on.

It is necessary that the trial arrangements of operating centers be chosen with great care, so that the comparison of the results of the various plans will give a direct comparison of the results of some possible program with some other possible program. In other

words, each plan must differ from some other plan by one variable only.

By reference to Fig. 6, it will be found that plan No. 1 assumes an office at the present "X" location and at the present "Y" location. A center has also been assumed at the "Z" wire center which has been calculated as outlined above.

Plan No. 2 is exactly the same as plan No. 1 except that an "M" center has been added at the wire center of the "M" area. A comparison of plan No. 1 with plan No. 2 will therefore give a direct indication as to the economies of an "M" operating center.

Plan No. 3 is exactly the same as plan No. 1 except that a center has been added at the wire center of the "A" area. A comparison of plan No. 3 with plan No. 1 will, therefore, give a direct indication of the economies of having an operating center in the "A" area.

While plan No. 2 and plan No. 3 will give an indication as to the economies of an "M" or an "A" center, the downtown "X" center will be smaller, of course, if both the "M" and "A" centers are in existence than if only one of these centers were in existence. In order to check whether this would make any material difference in the economies of the arrangement of operating centers, a further plan No. 4 was prepared which assumes both an "M" and an "A" center.

Referring again to Fig. 6, it will be found that the first item of cost to be considered is that of subscribers lines or in other words, the cost of the conductors (including conduit) to connect the subscribers' telephone instruments with the operating center. The conductor requirements are determined for each plan, and suitable annual charges are applied. The annual cost of subscribers' lines is larger for any plan which has fewer centers since the only economy which can be obtained by opening an additional operating center, is a reduction in the cost of the subscribers' lines.

Whenever an additional center is added, it is necessary to connect this center by means of trunks to all the other centers in the city so that subscribers served from this new center can talk to any subscriber served by any other center. The trunk cost, therefore, will increase each time a center is added. An estimate is made of the flow of traffic between the various centers, from which estimate the number of trunks is derived. Knowing the grade trunk required to give proper transmission, the cost may be inferred.

Central office equipment is placed in the building at each operating center, of course, to furnish talking power to the subscribers and to furnish a means of switching connections between subscribers. The cost of the central office equipment increases somewhat when an additional center is added, due to the fact that it is necessary to provide a power plant and other common items of equipment for each building, and due to engineering and installation costs. In order to arrive at the equipment costs an estimate is made of the lines, terminals, originating calls, and calls trunked to and from

other units of equipment, based on the estimated telephone development for the 20 year period. From these data, the requirements for various parts of the equipment are calculated and priced.

If a new operating center is opened, sufficient equipment would not be installed to last for the 20 year period covered in our growth estimates, of course, because the carrying charges on the idle equipment would be prohibitive. A considerably smaller amount of equipment would be installed, and additions would be made from time to time as required by the increasing number of subscribers.

An engineering and installation cost is involved each time an addition is made to this central office equipment. If more centers are added in a town, therefore, we will be adding equipment for growth to each of these centers, resulting in more but smaller additions. These engineering and installation costs do not decrease in proportion to the decrease in size of the addition; that is, these costs for a 2000 terminal addition will, in general, be more than one-half the cost for a 4000 terminal addition. Thus more centers will result in greater engineering and installation costs. These costs are capitalized, of course, as a part of the cost of the equipment.

In like manner, it is found that the operating costs, such as maintenance or other labor, and the costs of buildings and land are greater whenever an additional center is placed in a town. The maintenance labor is estimated by determining the number of men required and their salaries. Building costs are estimated by determining the required building volume.

Let us assume that the summation of the above annual charges for our problem indicates that Plan II and Plan III are each lower than Plan I (Fig. 6) and that Plan IV is also lower than either Plan II or Plan III. This indicates some economies for operating centers in the "M" and "A" areas as of 1947. As previously stated, the above calculations are based largely on being able to construct an ideal plant as of 1947 with no penalties due to the plant now in service. This is obviously an impossible condition and the above results, therefore, can be taken as only a broad general indication of the best method of serving the town. Obviously the above results give no indication as to when an operating center should be opened. It will be necessary to study each major move individually with the above results in mind.

Since there is already a center in the "M" area and the subscribers' cable is centered to this location, and since the indications are favorable to a center in this area for the 1947 period, there is little question but that the center should be continued. The present equipment is manual and the next big problem in this area will be to determine what to do when the manual unit is filled and cannot be extended without some major move.

In the "A" area (at present served from the down-

town building), our assumption as to annual charges indicates that at some time it will probably be advisable to open an operating center. We have no indication, however, concerning at what time this center should be opened. We know from past experience that in general the best time to open a new center in an area is that time at which it would be necessary to make some major move if the center were not opened. For example, since the "A" area is fed from the downtown building, a time might arise when it would be necessary to make some major move downtown to handle the growth, such as a large building extension, with the possibility of postponing this move if a center were opened in the "A" area. On the other hand, the cable or conduit which feeds the "A" area might become filled so that a very large expenditure would be involved to reinforce these facilities if we continue to feed this area from the downtown building.

Let us assume that the latter condition exists in the "A" area. The feeder cables serving the section are located in conduit, the last duct of which will soon be used. It would be necessary to reinforce this conduit in the latter part of 1928 and place additional cable if the section were fed from the downtown building. This reinforcement will be expensive due to the fact that a portion of the reinforcement will involve rock digging. Knowing from the above studies that a center in the "A" section will probably be economical at some future time, the question immediately arises as to whether it would not be better to open this center in 1928 rather than to make the expensive conduit reinforcement and add more cable.

In order to solve this problem, reference is made to the estimated telephone development of the "A" area and the downtown area for the 20 year period and the intermediate periods, as developed from the commercial survey data. Based upon this estimated development, an estimate is made of all the building and equipment additions which would have to be made downtown between 1928 and 1947 both with and without an "A" center. An estimate is also made of the expenditures for conduit and cable which would be required, between 1928 and 1947, both with and without an "A" center. An estimate is made of the amount of equipment and the size of the building which it would be necessary to provide if the center were opened in 1928 and an estimate is also made of the additions which would have to be made to this building and equipment between 1928 and 1947. These various amounts of plant are priced and the annual charges are inferred. Since the investments and annual charges would vary between plans throughout the period between 1928 and 1946, the annual charges are placed on a present worth² basis. The following table indicates the results of this present worth study.

2. The present worth of a given sum of money due at the end of a given time is the sum that, put at compound interest for the given time, will amount to the given sum when due.

PRESENT WORTH 1929-1947

	Plan I Operate from "X"	Plan II Open New Office
Aerial cable.....	\$ 55,966	\$ 45,812
Underground cable.....	187,243	41,706
Underground conduit.....	59,868	—
Salvage on displaced plant.....	-26,559	-42,521
Building including house service. . .	28,922	108,678
Land.....	—	4,306
Central office equipment.....	334,998	477,597
Excess maintenance.....	—	69,883
Number changes.....	2,184	14,500
Traffic saving.....	—	-8,496
Excess inter-office trunks.....	—	10,764
Total.....	642,622	722,229
Excess.....	—	79,607

NOTE: The above does not indicate the total cost of serving the area, of course. The cost of much of the plant which will be required under either plan, has been omitted as being common to both plans.

This investigation, as summarized on the chart, tells us that, in so far as the various factors can be evaluated, the center should not be opened in 1928 but that the conduit should be reinforced and cable added instead. These data do not tell us when the center should be opened. It will be necessary to watch this situation in the future and consider the problem again from time to time in much the same manner as above.

Since the data are available, the annual charges both with and without the "A" center are obtained for 1928 and for 1946. These annual charges are then

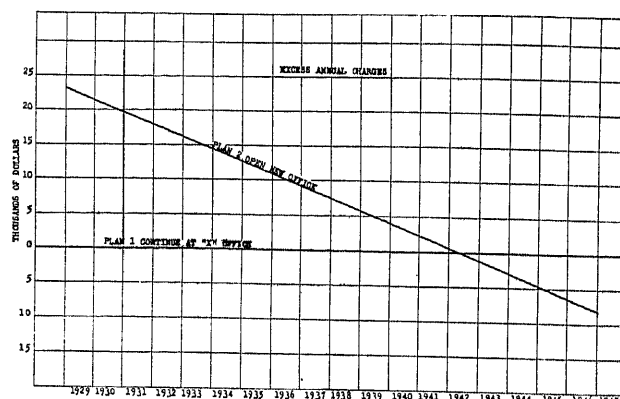


FIG. 7

plotted upon a graph as given in Fig. 7 and the annual charge points are connected by a straight line. It is appreciated, of course, that this annual charge will not be a straight line between 1928 and 1946 but will be irregular due to the periodical additions of plant and the straight line, therefore, is only a general indication. Our studies have told us, however, that if the "A" area grows as estimated, and if there are no unforeseen changes in the art, we will probably find it advisable to open an operating center in this area at some future date.

The above discussion on the determination of the proper number of operating centers for a town and the determination of the wire centers for these operating

centers has indicated that the location for a telephone building is determined by the number and location of the subscribers to be served by that building. The number and location of the telephone subscribers is in turn the result of many factors, such as the topography of the town, real estate development, transportation, etc. It is apparent, therefore, that it will at times be necessary to build a telephone building in a residence area. When this is necessary, however, special care is taken to build a suitable and attractive building. The general architectural appearance is made to harmonize with the neighborhood. The set back in general use in the neighborhood is observed. Generous yards are provided, and these yards are made attractive by suitable treatment with shrubbery. In other words, every effort is made to make the building a welcome addition to the neighborhood.

The studies illustrated above have enabled us to reach the following conclusions:

1. The wire center in the "Z" area for the 1947 development is indicated by our calculations to be a considerable distance south of the present building. When it becomes necessary to erect a new building in this area, the trend of the future development, therefore, indicates that we should consider a location for the new building considerably south of the present building. The present building, of course, has been in service many years and was located as nearly as possible on the economical center for the development to be served by this building during its life. The new building, however, will serve a somewhat different area, and the trend of future development is towards the south.

2. We can conclude that there should be an operating center in the "M" area. The conditions in this case are somewhat similar to those in the "Z" area and will call for similar treatment in the light of conditions in the area.

3. We have determined that, from an economic standpoint, the conduit which feeds the "A" area should be reinforced in 1928 and additional cable placed between the area and the downtown building, thus deferring the opening of a new center in the "A" area for the time being.

4. We have obtained indications that it will probably be economical at some future date, to open an "A" center. It will be necessary to keep this in mind and make a further study of this question whenever it is necessary to make some major move which could be postponed if the center were opened.

Mention has been made above of the introduction of dial equipment in some of the offices. The question of when and how dial equipment should be introduced into an exchange is one which must be very carefully considered. As a general rule the most favorable time for the introduction of dial equipment is when it would be necessary to make some major move to care for the further growth in the area served by the operating center.

In developing the program to be followed in offices which are still on a manual basis consideration must, of course, be given when the necessity for a major move arises, to the question as to whether the use of this type of equipment should be extended for a further period or whether the dial type should be introduced.

It would, of course, be unwise from a physical and financial standpoint in one of the larger cities, St. Louis, for example, to undertake to change all of the manual equipment to dial equipment at one time. Since the manual equipment is entirely satisfactory for present conditions and much of it will be continued in service for some time it becomes necessary to devise interconnecting equipment whereby new operating centers as they are introduced may be of the dial type and be connected with and operated with the existing manual equipment. All of this has been satisfactorily accomplished and the costs of such equipment are reflected in the various cost studies.

There are two types of dial equipment, the so-called "panel" type equipment and the so-called "step-by-step" type equipment. Panel equipment has been designed primarily to meet the conditions in the larger exchanges, such as St. Louis, while step-by-step equipment is usually employed in the medium sized and smaller exchanges.

Referring to the above problem in the "M" and "Z" areas, careful studies made some time ago have indicated that the growth can be handled economically without any major moves by adding manual equipment. A major move will be required at "Z" when the manual unit is filled, when it will either be necessary to start a new manual unit or to start a new dial unit. Our studies outlined above indicate that if a new center is opened in the "Z" area, the building should be located about a mile south of the present building.

The problem in the "Z" area can be stated specifically as follows:

- a. The "Z" area is served from one building which is considerably off the wire center for future development, for reasons previously outlined. The building houses one manual unit which will soon be filled, making it necessary to provide some major relief.

- b. The preliminary indications are that the "Z" area should be served from one building in the vicinity of the wire center, overlooking for the moment the factors involved in making such a move.

Questions:

- a. Should this new unit be located in an addition to the present building to conserve existing plant, or should a new building be erected nearer the wire center for the purpose of decreasing future investments in plant to care for future growth?

- b. Should the new unit be of the manual or dial type?

- c. In case the new unit is to be of the dial type, should enough equipment be installed for growth

only, or should enough be installed to displace the manual unit?

In order to answer the above questions, it will be necessary to consider in detail each of several possible construction programs. Having determined the factors involved in the various possible programs, the engineer proceeds with the analysis of each of these programs. Possibly one or more programs can be eliminated due to practical considerations, and careful cost studies may eliminate other programs from an economic standpoint. In case cost studies are necessary, they will probably be of the present worth type, which was outlined above, for use in the question of opening a new center in the "A" area. In fact, this problem is somewhat similar to the problem outlined above for the "A" area, except that this problem is considerably more complicated, due to the presence of a building in the area. Taking all factors into account, one program is finally determined to be the most favorable to meet the needs of the particular situation.

Another type of problem has to do with the question of economic allocation of the transmission loss between the subscribers' plant and the trunk plant. This is determined by what are known as "loop and trunk studies." The data developed in connection with the commercial survey mentioned at the beginning of this paper together with comparable estimates of inter-office truck requirements, are largely used in the solution of this problem.

This problem is generally solved for an estimated development of a considerably less remote period than the 20 year figure used in some of our work. This is because the results of these studies are used for immediate engineering of extensions to the cable plant. The life of this plant in general is less than the life of central office buildings, and moreover it is relatively easy to make some adjustments in grade of conductors by making cable throws.

The estimated development indicates the numbers of lines which will be in service in each central office area at the future date selected and the lengths of these lines. Knowing the number of lines, the number and holding time of the calls flowing between offices are estimated and from this, the numbers of inter-office trunks on the various trunk routes are calculated.

In order that subscribers can talk satisfactorily in any exchange, the plant must be designed to conform with generally recognized transmission standards, these standards being set after individual consideration of all the factors peculiar to any one area. These standards represent a grade of transmission which experience has indicated will be thoroughly satisfactory to the subscriber and at the same time permit the development of an economical plant.

In a multi-center exchange area, the transmission loss is distributed principally between the subscribers' loops and the trunks, that of the station and central office equipment being relatively constant. In order to

attain the desired standards, consideration must therefore be given to designs which will economically apportion the loss between the two classes of plant. It would be possible to provide the cheapest subscribers' plant available and make up the required transmission in an expensive trunking plant or vice versa. Obviously, either procedure would not permit of obtaining the desired transmission with an economically balanced plant.

Knowing the numbers and lengths of the lines and also the numbers and lengths of the various inter-office trunks required, as outlined above, the costs of the trunk and subscribers' plants are estimated on an annual charge basis for various distributions of the loss between the two types of plant. The transmission losses are then by successive trial distributed between the subscribers' loops and trunks and the total annual charges are estimated. These estimates will indicate which distribution involves the minimum total annual cost for both plants. This procedure is carried through for each central office in the exchange. The portion of the transmission loss (in T. U.) assigned to the subscribers' loops in each central office area is called the loop limit for that office.

This whole study is, of course, based on an ideal plant in the same manner as in the studies to determine the ultimate number and arrangement of offices in the exchange. Actually, the existing plant may differ materially. After the study is made, therefore, it is necessary to consider the plant actually in service and its effect upon the indications of the study before the limiting loops are finally decided upon.

The preliminary planning of telephone exchange plant has been discussed above largely from an economic standpoint and the discussion may have given the impression that the economics of the problem are given undue consideration. Such is not the case. It is obvious that any construction program must be considered from other angles as well as the economic angles. For example, if one program will result in better service to the public than another program, the program which would result in better service will receive instant and sympathetic consideration, even though this program might not be quite as attractive from an economic standpoint as some other program. Some programs require large amounts of capital, labor, and material, and it is obvious that such programs should be spread out to best advantage over a period of years.

Any program must be considered carefully to be sure that it is thoroughly practicable from a construction and operating standpoint. It is also desirable that all existing plant be used to best advantage, and when such plant is in good condition and would continue to give good service, it is generally desirable that such plant be retained until it has lived a normal life. To do otherwise would use up capital and result in rearrangements and changes which might not be desirable, even though

such a course might show some small savings. In all of these considerations, of course, especially those involving rearrangements and changes, the factor of service to the public is given a very prominent place.

It is also important that the plans for the future extension of the plant be developed in a manner that will permit of a maximum of flexibility in caring for the future service requirements. Thus the characteristics of a plan must be such that suitable adjustments can be made economically in the event that the growth performance in the future varies materially from that upon which the plan was based. In other words, before commitments are made in line with any future plan, this plan is considered broadly from all angles and advantage taken of the knowledge and experience gained in the execution of similar plans.

It is hoped that the preceding outline of the broad general considerations of planning, together with the earlier outline of some of the economic features, will accomplish the purpose of this paper, which as previously stated is to give a general idea of the methods used in planning telephone exchange plants.

Discussion

E. N. Widen: In discussing Mr. Stephenson's paper, I will confine myself to only one of the important questions upon which it touches, namely, the importance of population forecasting. People constitute the telephone market; therefore, forecasts of the future growth in the telephone market of a community must be based upon a consideration of the probable changes in the number and character of its inhabitants. In the telephone business, the importance of forecasting the future demand for service can hardly be overemphasized for two reasons: first, an obligation rests upon a telephone company to deliver service when and where it is needed; second, sound population forecasts are essential if the losses incident to over-built or under-built exchanges are to be avoided.

The telephone plant, especially in large communities, is each year becoming less susceptible as a whole to radical changes in basic plans, a fact which further emphasizes the importance of appraising the future market carefully. Other utilities, including electric light and power companies, gas companies, and street railways, are faced with practically the same problem in estimating their future market. Incidentally, the need for population forecasting in city planning might be mentioned, a fact emphasized by the necessity now existing in many of our large cities for costly street-widening projects and the provision of plazas and parks in sections already built.

Business generally, I believe, has become more forward-looking. Manufacturing programs, sales plans, and financing arrangements of large concerns all are based more or less upon forecasts of the volume of business done. However, the importance of forecasting the future volume of business varies widely in different types of industries. A shoe manufacturer, for example, may be utterly mistaken in his ideas of the volume of business to be secured in certain communities; perhaps his expectations are much too high in some instances and much too low in others. Yet, because the manufacturer has no fixed capital investment in the particular communities, such errors in judgment may be of no serious consequences whatever.

Again, if a large distributor finds business below expectations in some of his markets and above expectations in others, he can, with no great inconvenience, concentrate his efforts on the better markets. But the problem is a different one for the telephone

company and other utilities. If a city grows far more rapidly than was anticipated, or if its growth comes in unexpected sections, the utilities serving it naturally require a period for planning and installing the facilities necessary to meet the unexpected conditions. In other words, the utilities, with their heavy fixed capital investments, have less flexibility than do most other kinds of industries.

Population forecasting is not a simple undertaking. On the contrary, it requires the most searching analysis of economic resources and economic trends. What most probably will occur to influence population changes is always the first consideration in forecasting the population of a community; sound forecasts cannot be based upon what could or should be done. Moreover, such forecasts cannot be made to rest upon a local point of view. The principal population-supporting activities of a community must be considered from a national and even an international point of view; such procedure ordinarily leads to less optimistic conclusions than those reached by mere local judgment, but they are more likely to be realized.

It must be recognized that cities and regions are in direct competition with each other for shares of the total growth of the country, and that comparative, not absolute advantages are the determining factors. Incidentally, I might mention that the Bell System, in order to improve its population-forecasting work, has undertaken systematic and comprehensive studies of economic changes affecting the number and distribution of the nation's population. As a phase of this work, in the South-western Bell Telephone Company, we are making economic surveys of each of the five states in which we operate.

In addition to forecasting the population of a community as a whole, the telephone company has the problem of forecasting the distribution of population within a city. For this purpose it is necessary to consider such questions as transit conditions, probabilities of transit improvements, the availability and desirability of vacant land, and the probable reconstruction and crowding, or perhaps thinning out of population in the older sections. Any forecast of future demand for service requires an appraisal or gradation of the market, with the present and future character of the population assigned to each small area of the city. All this is, of course, essential to the proper layout of the telephone plant. The analysis of the present and future market is likewise fundamental to the proper planning of a sales program.

Everyone recognizes that many uncertainties attend the making of population forecasts. We cannot estimate for accidents nor in long-range forecasting can we estimate for accelerations and delays due to temporary business conditions. Meticulous precision is impossible, but we believe that a working knowledge of conditions in the future is not only a possible and practical thing, but something essential to the intelligent conduct of the telephone business.

G. J. Vande Steeg: Mr. Stephenson has stated that it would be unwise from a physical and financial standpoint to undertake a complete conversion in our larger cities from manual to dial-type equipment at one time. Several elements, of course, contribute toward making such a course unwise. One of these is the manufacturing situation and it may be well to discuss briefly some of its aspects.

For the purpose of discussion, we will include, under manufacture, all of the activities in connection with the provision of materials or apparatus, until these are made available to a telephone user. We start, then, with the purchase and assembly of raw materials. This is an extremely important item as the Bell System factories annually require vast quantities of almost all kinds of materials. The yearly requirements for some of the more common and familiar items will indicate the magnitude of this phase of the manufacturer's problem. Among the leading items are steel, 22,000,000 lb.; antimony, 2,000,000 lb.; silk and cotton yarns, 4,000,000 lb.; lumber products, 24,000,000 board

ft. The manufacturer of lead-covered cable each year requires 170,000,000 lb. of paper, lead, and copper. Should a complete conversion to dial equipment at one time be found desirable in our larger cities, simultaneous conversions in other large cities in the country might be reasonably expected, resulting in abnormal demands for raw materials with the usual reactions on prices.

The processes of converting raw materials into items useful in the telephone plant are varied and in some cases extremely complex, requiring the services of a personnel ranging from unskilled labor to highly specialized and trained technicians. In the case of dial central-office equipment, the manufacturer installs the equipment. This work requires a force of trained experts and special testing apparatus, to insure satisfactory operation of the equipment when it is turned over to the telephone company.

These points are brought out to indicate the manufacturers' connection with conversion projects so that the desirability of scheduling these projects to insure as nearly as possible a uniform factory load may be apparent. In order to permit the manufacturers to procure raw materials advantageously and to lay out a uniform program of manufacture and training of factory and installation personnel, it is essential that the major conversion projects be scheduled far enough in advance and the program planned to avoid as far as possible excessive peaks in factory loads. Such a program benefits the purchaser in that a better product can be obtained at a lower cost.

It is apparent, I believe, that the manufacturing problems should be given weight in laying out a conversion program. The difficulties and penalties are, however, not controlling and should the desirability of a complete conversion be indicated by thorough consideration of all the factors, the manufacturing difficulties can be overcome.

H. R. Fritz: Mr Stephenson, in his paper, referred to loop and trunk studies which are made to determine the economical distribution of the exchange plant between trunks and subscribers' loops in multi-office areas. Such studies assume the use of the most efficient type of subscribers' instruments available at the time. Such an assumption is necessary in order that the most economical use may be made of the cheaper small gage cable.

Continuous improvement has been made in the efficiency of transmitters, receivers, and in the coordinated design of subsets. From time to time, there are made available instruments of such improved efficiency, which are introduced into the plant. The result is that there are now in use several instrument combinations which differ considerably in transmission efficiency. As

the limiting loops are established on the basis of using the most efficient type of apparatus, it is obvious that these several types of instruments cannot be used in an indiscriminate manner. To do so and still maintain the necessary transmission standard would mean that the cable plant would have to be designed for the least efficient of the sets.

To avoid this uneconomical procedure and still permit the efficient use of available types of instruments, it is the practise to establish definite zones in each exchange area for the several instrument combinations. Basing these zones on the use of 24-gage cable, the least efficient subsets are restricted to the zone nearest the central office.

The limit of this inner zone is determined by the length of 25-gage cable, which can be used without exceeding the limiting transmission for any particular office. Beyond this limit, a second zone is established, in which subsets of the next higher grade are used. Finally, a third or outer zone requires the use of the most efficient types of instruments. When the limiting loop has been reached with 24-gage in this zone, use is made of combinations of 24- and 22-gage, all 22-gage, combinations of 22 and 19-gage, and finally all 19-gage cable. Loops of such length that the desired transmission cannot be given with 19-gage conductors and the most efficient type of instruments, are given special consideration and the most suitable means for treating them are applied.

This method of zoning instruments permits the maximum and most economical use of the several gages of exchange cable without having to abandon the use of the less efficient subsets. As future improvements in the efficiency of subsets become available, it will be possible to extend the use of small-gage cables, resulting in further economies in the cost of exchange plant.

As mentioned in Mr. Stephenson's paper, the loop and trunk study envisages an ideal plant. The same is true of the instrument zones. Actually, of course, the existing cable plant is not distributed in the manner assumed in establishing limiting loops and laying out the zones. As a rule, there is in the plant a considerably larger amount of 22- and 19-gage cable than required in the ideal plant. This may lead to the temporary establishment of limiting loops and instrument zones different from the ideal. Also, ringing and common battery supervision requirements may modify the use of an ideal cable plant based only on transmission. However, all new plants and additions to existing plants are engineered to conform with the ideal arrangement. Instruments are zoned in the same manner, either on a routine basis or by wholesale changes, depending on circumstances.

A Thermal Method of Standardizing Dielectric Power Loss Measuring Equipment

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Synopsis.—After a brief review of the need for reference standards in dielectric power-loss measurements at high voltage and commercial power frequencies, this paper describes a thermal method for measuring dielectric power loss in cable, utilizing the sheath temperature rise associated with the flow of heat due to the power loss within the sheath. Sources of error are discussed briefly, and results are given

in comparison with measurements of dielectric power loss by the reflecting astatic electrodynamicometer wattmeter using an air capacitor for phase-angle compensation.

In connection with the investigation, certain possible errors in dynamometer measurements are noted, particularly the effect of humidity on power loss in the air capacitor.

GENERAL

FOR some years, engineers interested in the measurement of dielectric power loss at high voltage and commercial power frequencies, such as in paper-insulated cable, have felt the need for suitable means by which such measurements could be standardized. Until stable standard loads as described by Mr. F. M. Farmer at the Madison Regional Meeting of the Institute in 1926³ were prepared and circulated among the various laboratories and factories interested, no such reference standards were available. These loads are sufficiently permanent to promise substantial agreement up to 20 kv. among those making dielectric power-loss measurements, which was not the case when cable samples were exchanged for this purpose. It is hoped that similar standard loads will be developed for higher voltages. These, however, are reference standards only. Dielectric power-loss measurements should be standardized in terms of well established units if possible.

It is considered that a check on dielectric power loss may be made with considerable accuracy by examining the heat appearing in the dielectric under consideration. The methods that occur to one as promising are either (1) a flow calorimeter or (2) the comparison of surface temperature rise of two samples under similar conditions,—one having dielectric power loss; the other, a source of heat easily measured with the desired accuracy, such as d-c. ohmic power loss in the conductor. When the temperature rises are equal, the dielectric power loss in the former is taken equal to the ohmic power loss in the latter. The symmetrical geometry of lead sheathed cable and the ease of making measurements on a short section of a long cable (thus avoiding end effects), led to the adoption of the latter method which will be known in this paper as "comparison of heating." Results of preliminary measurements by comparison of heating at about 35 kv. three-phase were presented by Mr. E. S. Lee in the discussion of the

Symposium on Dielectrics and Power Factor Measurements held at the Niagara Falls Regional Meeting of the Institute in 1926.⁴ The present investigation extends this method to single-phase measurements at 90 kv., and introduces refinements in the apparatus and method.

It should be noted that our immediate interest in this work was the detection of any constant error in the dynamometer wattmeter equipment as used for the measurement of dielectric power loss in high-voltage cable.⁵ Due to this interest, several other phenomena not closely connected with the thermal measurement of dielectric power loss, especially the fairly definite loss in the air capacitor at high relative humidity, were examined and are reported here.

This paper is presented that others interested in dielectric power-loss measurements at high-voltage and commercial power frequencies may avail themselves of our experiences with this method as a means of checking dielectric power-loss measuring equipment.

DESCRIPTION OF APPARATUS

Comparison of heating requires the measurement of the ohmic power loss in the conductor of one cable which produces nearly the same sheath temperature rise as that of a similar cable to which alternating voltage is applied across the insulation, the cables being under like conditions for heat flow to the surrounding medium; that is, two like cable samples with suitable terminals are required, mounted in some medium that provides approximately constant ambient temperature and like conditions for heat flow from the two cables. Means must be provided for the measurement with necessary accuracy of the small temperature difference between the two sheaths. Actual temperature rises are not needed if the condition of constant equal ambient temperature and thermal emissivities constant in time can be maintained. Air is not necessarily the best medium of those suggested to meet these conditions, but it was found quite satisfactory in the apparatus described below.

A room with thermostatically-controlled heaters was available for the test. With the thermostat set for 33 deg. cent., and the air in the laboratory at about 27 deg. cent., (normal summer condition), the air in

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the lower part of the room went through cycles of about 20-min. duration with a maximum temperature difference of 0.6 deg. cent. The average temperature of the various cycles varied through a range not exceeding 0.1 deg. cent. with the latter part of the day usually a few hundredths of a degree hotter. In this room were placed two 30-ft. (9.2-m.) lengths of 750,000-cir. mil (380 sq. mm.) stranded-conductor lead-sheathed cable, insulated with 0.750-in. (19 mm.) oil treated

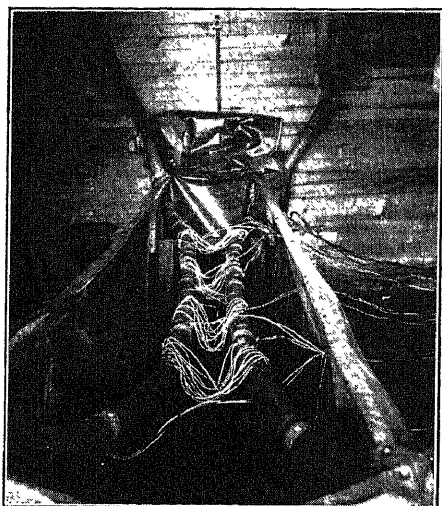


FIG. 1—CABLE SAMPLES ARRANGED FOR DIELECTRIC POWER LOSS MEASUREMENT BY COMPARISON OF HEATING

paper; 10-ft. (3.05 m.) measuring sections at the middle of each length were insulated by cutting out about $\frac{3}{8}$ in. (0.9 cm.) of lead and filling the space with gum rubber. These measuring sections were supported near the floor (Fig. 1) and enclosed in a tight paper box. This paper box (shown with the top rolled back in the figure) served to reduce the cyclic variation of ambient temperature from 0.6 deg. cent. to less than 0.2 deg. cent. The cable ends were carried up to suitable terminals on the roof and the sheaths beyond the measuring section, together with a network of piping and low-voltage wiring conduit on the ceiling, carefully grounded, thus providing electrostatic shielding of the measuring section.

Two schemes of temperature measurements were used. Four sets of thermopiles, each consisting of 20 copper ideal junctions in series, 10 "hot" junctions embedded in the sheath of one cable and 10 "cold" junctions in the other, were distributed along the measuring sections of the cables to permit reading temperature differences. The second scheme consisted of five resistance temperature detectors made of 10-mil (0.065 sq. mm.) enameled copper wire wound in contact with the sheath of each cable and covered with a strip of 0.010-in. (0.25 mm.) horn fiber. The thermopile e. m. fs. were obtained from observation of the deflection of a galvanometer of suitable sensitivity in series, taking deflection in both directions.

A potentiometer was used to measure resistance

temperature detector resistances. It appeared to have some advantage over a bridge for the low-resistance (10 ohms) detector used.

Direct current was circulated through the conductor of one cable from a motor-generator run from a "constant voltage" supply, with manual control to supplement the voltage regulator. The power dissipated in the cable conductor was measured with portable ammeter and millivoltmeter carefully calibrated. Alternating high voltage of 60-cycle frequency was impressed on the other cable from a 70-kv-a. testing transformer supplied from a generator of good wave form. Voltage measurement was by means of a portable dynamometer type voltmeter connected to the voltmeter coil of the testing transformer and checked against the potential transformer and voltmeter of the dielectric power loss dynamometer wattmeter equipment.

HEAT FLOW

Two questions may well arise here concerning the necessity for approximately constant ambient temperature and the possibility of error due to axial flow of heat along the conductor. Constant ambient temperature is necessary because the dielectric power loss in paper-insulated cables at a given voltage changes with temperature and because, of the two cables, the one heated

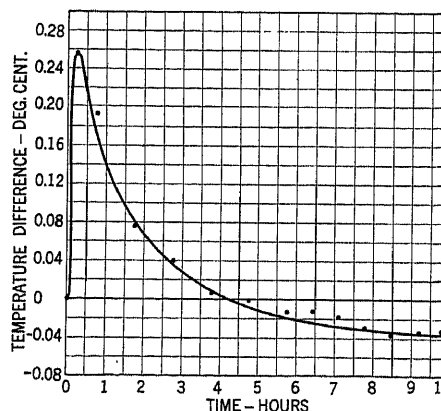


FIG. 2—TEMPERATURE DIFFERENCE BETWEEN CABLE SHEATHS AS A FUNCTION OF TIME

Ordinate is temperature of cable sheath A minus temperature of cable sheath B, with dielectric power loss in cable A nearly equal to ohmic loss in conductor of cable B

by dielectric power loss will respond more rapidly to changes in ambient temperature than the one heated by copper loss. Fig. 2, showing temperature difference as a function of time between two cables having dielectric power loss in one very slightly less than the ohmic power loss in the conductor of the other, illustrates this.

The possibility of error due to axial flow of heat along the conductor may be considered from the standpoint of the following approximate analysis of steady state conditions:

Refer to Fig. 3, which shows a length, $2L$, of single-conductor cable whose axis lies along the x-axis and whose center is at the origin.

- a = radius of conductor. (cm.)
 b = outer radius of insulation. (cm.)
 α = thermal conductivity of conductor (calories per second through a cm. cube per deg. cent. between faces)
 β = thermal conductivity of insulation. (calories per second through a cm. cube per deg. cent. between faces)
 θ_1 = temperature of a point on surface of conductor. (deg. cent.)
 θ = temperature at a point in insulation, coordinates x, r . (deg. cent.)
 ρ = source of heat, calories per cu. cm. per sec. in conductor.

Neglect radial temperature drop in conductor.

Neglect axial temperature drop in insulation.

Boundary conditions. $\theta = 0$ at $r = b$

$\theta = \theta_1 = 0$ at $x = L$

$$\frac{d\theta_1}{dx} = 0 \text{ at } x = 0$$

Take a disk element of small thickness Δx ; the flux

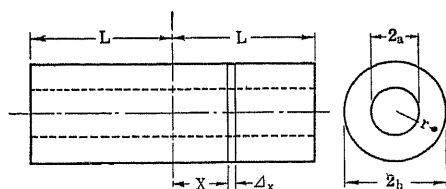


FIG. 3—DIAGRAM FOR AXIAL HEAT FLOW CALCULATIONS

of heat in the radial direction out of the element⁶ equals ΔH_r

$$\Delta H_r = \frac{2\pi\beta\theta_1}{\log \frac{b}{a}} \Delta x \quad (\text{calories per sec.})$$

The flux of heat in the axial direction out of the element equals ΔH_x .

$$\Delta H_x = -\pi a^2 \alpha \frac{d^2 \theta_1}{dx^2} \Delta x \quad (\text{calories per sec.})$$

Heat appearing in element = $\pi a^2 \rho \Delta x$ (calories per sec.)

Then, since the heat leaving the element equals the heat appearing in the element,

$$-\frac{d^2 \theta_1}{dx^2} + \frac{2}{a^2 \left(\log \frac{b}{a} \right) \alpha} \theta_1 = \frac{\rho}{\alpha}$$

Solving and substituting boundary conditions

$$\theta_1 = \theta_m \left(1 - \frac{\cosh wx}{\cosh wL} \right)$$

where

$$w = \left(\frac{2\beta}{a^2 \left(\log \frac{b}{a} \right) \alpha} \right)^{1/2}$$

and θ_m = temperature of conductor in an infinitely long cable with the same ρ in its conductor; i. e.,

$$\theta_m = \frac{\rho a^2 \log \frac{b}{a}}{2\beta}$$

In this cable, w = approx. 0.028

α = approx. 1.0 L = 460 cm.

β = approx. 500×10^{-6} wL = 13

At the end of the measuring section, $x = 152$ cm., and
 $w x = 4.3$

$$\theta_1 = \theta_m \left(1 - \frac{\cosh 4.3}{\cosh 13} \right) = 0.9993 \theta_m$$

That is, the conductor temperature at the ends of the measuring sections of these cable samples is 0.999 times the temperature that would be reached if there were no axial flow of heat. Thus, for our purpose, flow of heat may be regarded as radial.

PRECISION OF MEASUREMENT

D-c. power input measurements, as such, call for no further comment. They are of the precision usually obtained with portable instruments and ordinary care. It is necessary to note, however, that, with our equipment, this power input could not be held constant during a heat run as closely as it could be read on the instruments. Momentary departures from the desired value of power input were as great as one and one-half per cent. The same figure holds for departure from the desired value of voltage squared on the cable having dielectric loss. It is believed that over a short period, the mean power was held to within one part in two hundred, though one per cent is reported here as a conservative value for probable error in holding constant power on each cable separately.

Cable charging current, although not entering into the determination of dielectric power loss, was measured, using an electro-dynamometer ammeter with an accuracy of one per cent. The same value of current at a given voltage, obtained from a series of determinations, was used in calculating all power factors at that voltage.

Temperature differences by thermopile were read by a galvanometer. The over-all sensitivity was 0.0015 deg. cent. per mm. deflection. Errors due to thermal e. m. fs. in the galvanometer and series resistance, (used to secure proper damping), were eliminated by reversed readings. Connection to the thermopiles was made by means of copper braid clipped directly to the copper wire leads from the thermopiles. There is here a source of possible thermal e. m. fs. not eliminated by reversed readings. This source of error was investigated and found small as compared with one mm. deflection.

In view of the fact that the resistance temperature detectors were read one at a time, it was necessary to follow a scheme of checking back, reading first a detector on cable A, then one on cable B, then back again to A, in order to avoid errors due to the small cyclic variations in ambient temperature previously

mentioned. This variation amounted to about 0.03 deg. cent. at the detectors (0.2 deg. cent. in the air). The sensitivity was about the same as for thermopiles, *i. e.*, readings could be taken quite rapidly to 0.002 deg. cent. Incidentally, the labor of computation is considerably greater with resistance temperature detectors.

Sensitivity of this order, since it was easily obtained, was considered desirable even though it was a little better than the accuracy with which temperature rises could be held; this is, 0.002 deg. cent. represented about 0.001 watt per ft. length of cable, or not over one-fourth of one per cent of the loss in the cable. Control of loss was not quite so close; say, less than one per cent. It is believed that the cyclic variation of ambient temperature led to no constant errors, though it undoubtedly increased the deviation of individual readings from the mean.

Measurements of dielectric power loss on this cable were made with the dynamometer wattmeter measuring equipment under temperature conditions as nearly like those obtaining on comparison of heating as possible. This, together with the close agreement between various dynamometer wattmeter measurements made over a period of five weeks, is believed to eliminate the possibility of serious error due to change in dielectric power loss in the samples. These measurements are recorded in Table I.

TABLE I
DYNAMOMETER WATTMETER MEASUREMENTS OF POWER
FACTOR OF CABLES ARRANGED FOR COMPARISON
OF HEATING:

Power factor. Cable A						
Date	45 kv.	60 kv.	75 kv.	82.5 kv.	90 kv.	100 kv.
8-2	0.0034 ₀	0.0034 ₅	0.0035 ₃	..	..	..
8-24	0.0032 ₈	0.0034 ₀	0.0033 ₆	0.0033 ₆	0.0033 ₅	..
8-25	0.0033 ₆	0.0032 ₃	0.0033 ₉	0.0030 ₈	0.0032 ₄	0.0034 ₆
9-30	..	..	0.0032 ₆	0.0032 ₅	0.0032 ₅	..
10-1	..	..	0.0032 ₈	0.0032 ₀	0.0031 ₈	..
Average			0.0033 ₅	0.0032 ₂	0.0032 ₅	

Power factor. Cable B						
Date	45 kv.	60 kv.	75 kv.	82.5 kv.	90 kv.	100 kv.
8-2	0.0034 ₂	0.0031 ₁	0.0034 ₂	..	..	..
8-24	0.0033 ₄	0.0033 ₅	0.0034 ₇	0.0035 ₂	0.0035 ₆	..
8-25	0.0034 ₀	0.0033 ₀	0.0035 ₃	0.0034 ₉	0.0035 ₉	0.0037 ₈
9-30	..	..	0.0033 ₂	0.0033 ₅	0.0033 ₆	..
10-1	..	..	0.0032 ₃	0.0032 ₃	0.0032 ₈	..
Average			0.0034 ₁	0.0033 ₉	0.0034 ₂	

As a numerical value for error in any one measurement of dielectric power loss by comparison of heating, assume equal weights for one per cent error in holding d-c. power input constant, one per cent error in holding square of impressed voltage constant, and one and one-half per cent error in power corresponding to one-half the cyclic variation of sheath temperature (0.03 deg. cent.)

$$((0.01)^2 + (0.01)^2 + (0.015)^2)^{1/2} = 0.0206$$

or two per cent expected error in final dielectric power-loss measurement. In this cable sample, this is about two-thirds of 0.0001 power factor.

The error in a dynamometer wattmeter measurement, assuming correct phase-angle error compensation, is

taken equal to 0.0002 power factor for samples of this size with the dynamometer wattmeter equipment used in this investigation. Thus, a difference between power factor calculated from dielectric power loss by comparison of heating and power factor from dynamometer wattmeter power measurement, greater than 0.0003 power factor, would call for explanation.

THEORY CONCERNING HEAT EMISSION

Consider two cables, A and B, set up as described and in thermal equilibrium.

P = loss, watts per cm. length in A

Q = loss, watts per cm. length in B

a = "thermal emissivity" of A, watts per cm. length per deg. cent.

b = "thermal emissivity" of B, watts per cm. length per deg. cent.

α = temperature rise A, deg. cent.

β = temperature rise B, deg. cent.

θ = $\alpha - \beta$

$P = a\alpha$

$Q = b\beta = b\alpha - b\theta$

$$Q = P \frac{b}{a} - b\theta \quad (1)$$

or, if P is unknown, Q known,

$$P = Q \frac{a}{b} + a\theta \quad (2)$$

a and b may be thought of as somewhat fictitious emissivities invented as a tool for handling quantitatively the consistent small differences in temperature rise that appear when two pieces of cables from the same reel are laid side by side and dissipate equal amounts of power.

These differences would not be expected to be the same for any two sets of temperature detectors applied to the lead sheath but they are considered constant in time if the apparatus is not handled or moved; that is, values of a , b , and θ (Equations (1) and (2)) obtained with one set of temperature detectors differ from values obtained with another set of temperature detectors, yet resulting values of P or Q might be approximately the same.

EXPERIMENTAL RESULTS

Five runs with direct current in each cable were made to provide data for the determination of a , b , and

$\frac{a}{b}$ although only two were necessary to solve for these

constants from equations (1) or (2). The additional runs were made to verify their constancy in time. Results are shown in Table II.

These were followed by six runs, (a "run" referring to the maintenance of a definite current in one cable and voltage on the other cable for the time, about 10 hours, required to reach approximate thermal equilibrium), the results of which are tabulated in Table III.

In this table "th" refers to thermopile determinations. "R. T. D." to resistance temperature detector determination, and "Dyn." to measurement of dielectric power loss by dynamometer wattmeter with air capacitor for compensation. θ refers to equations (1) and (2). Note that one run was made on each cable at each voltage as a further precaution against error or change

at high relative humidity is under "Effect of Humidity on an Air Capacitor."

REVIEW OF COMPENSATED DYNAMOMETER WATTMETER MEASUREMENT OF DIELECTRIC POWER LOSS

A brief review of the compensated dynamometer wattmeter method of measurement of dielectric power

TABLE II
DETERMINATION OF EMISSIVITY
(Symbols refer to equations (1) and (2))

Run no.	P	Q	Thermopiles				Resistance detectors			
			θ	a	b	$\frac{a}{b}$	θ	a	b	$\frac{a}{b}$
1.	0.0165	0.0165	0.008	0.0144	0.0146	0.990	0.026	0.0139	0.0142	0.980
2.	0.0165	0.0144	0.153							
3.	0.0129	0.0144	-0.093	0.0144	0.0146	0.990	0.026	0.0139	0.0142	0.980
4.	0.0155	0.0155	0.014							
5.	0.0172	0.0155	0.132	0.0144	0.0146	0.990	0.026	0.0139	0.0142	0.980

in a and b , the thermal emissivities. To aid rapid analysis, power factor results from this table are plotted in Fig. 4.

The two methods agree within nine per cent in any case, or within six per cent for average of all cases. This agreement is at about 0.003 power factor and represents a difference of 0.0002 power factor.

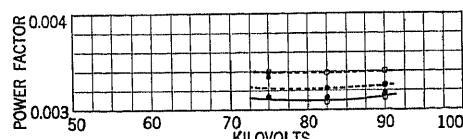


FIG. 4—GRAPHICAL COMPARISON OF POWER FACTOR MEASUREMENTS

• Cable A
• Cable B

Solid line (—) represents power factor determined from dielectric power loss measurement by comparison of heating.

Broken line (---) represents power factor from dynamometer wattmeter measurement of dielectric power loss

APPLICATION OF RESULTS

The comparison of heating measurements were made primarily as a precise check on the dynamometer wattmeter equipment for dielectric power-loss measurement. To make the fullest possible use of this check and to avoid the necessity for frequent repetition of comparison of heating measurements it became desirable that certain possible sources of error in the use of the air capacitor for phase-angle compensation of the dynamometer wattmeter be examined critically and the error reduced to a negligible amount. This work is discussed under two headings: (1) The effect of phase displacement between capacitor charging current and current through the dynamometer wattmeter current coils is under "Review of Compensated Dynamometer Wattmeter Measurement of Dielectric Power Loss," and (2) the fairly definite power loss in the air capacitor

loss will be of assistance in an examination of the errors which may arise, particularly those associated with high humidity. Fig. 5 shows the connection diagram of the capacitor and measuring circuit described heretofore.^{5,7} The guard rings G completely screen the low-voltage plates B from all electric fields other than that from the high-voltage plate A . Theoretically G should be at the same potential as B . Practically, grounding G introduces no error that can be read, as shown here. If the DPDT switch indicated on the diagram is thrown to position M , capacitor charging current less that part of it shunted through the capacitance and leakage resistance (see Fig. 6), from low-voltage plate to ground flows through the current coils of dynamometer D . Then Z_p may be adjusted in phase angle for zero deflection of the dynamometer, indicating a 90-deg. phase angle between dynamometer potential coil current and dynamometer current coil current. This will also indicate a 90-deg. phase angle between dynamometer potential coil current and the charging current of a pure capacitance if the air capacitor $A-B$ has negligible loss, the capacitance $B-G$ from low-voltage plates to guard ring is negligibly small and the leakage resistance R from low-voltage plates to guard ring is sufficiently high. If R is large compared to the impedance of the dynamometer wattmeter current coils, $R_c + X_c$, the phase difference between currents I_1 , and I_c , Fig. 6, may be regarded as X_c/R .

The minimum value found by measurement for R is 50 megohms. This observed value occurred at 70 per cent relative humidity and 26.5 deg. cent. The dynamometer wattmeter current coil reactance, X_c , is 93.5 ohms at 60 cycles.

$$\text{Phase difference} = \frac{X_c}{R} = \frac{93.5}{50 \times 10^6} = 0.000002.$$

Making the usual assumption concerning very small

angles that the angle, its sine, and its tangent, are all equal, this is a power factor error of 0.000002, which is clearly negligible as compared with 0.0002 power factor measurable with the dynamometer wattmeter equipment.

The capacitance $B-G$ from low-voltage plate to guard ring, including leads, is approximately $1300 \mu\mu f$. or 2-megohms reactance at 60 cycles. Dynamometer wattmeter current coil resistance, R_c , is 162 ohms. The phase difference between currents I and I_1 is then approximately

$$\frac{162}{2 \times 10^6} = 0.00008$$

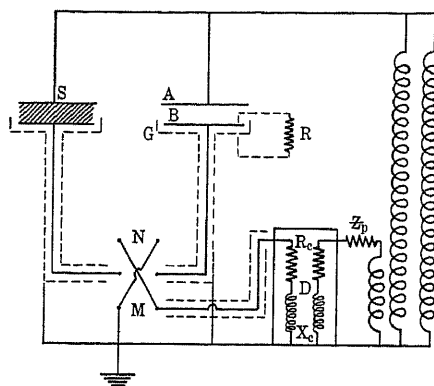


FIG. 5—CONNECTION DIAGRAM OF DIELECTRIC POWER LOSS MEASURING APPARATUS

- S Sample to be measured
- A High-tension plate of air capacitor
- B Low-tension plate of air capacitor
- G Guard ring and lead shielding
- R Leakage resistance from B to G
- D Reflecting astatic electro-dynamometer wattmeter
- Z_p Impedance of wattmeter potential circuit
- R_c Resistance of wattmeter current coils
- X_c Reactance of wattmeter current coils

This is a power-factor error of less than 0.0001, which is nearly significant but not large enough to read on the dynamometer wattmeter. Note that a similar phase displacement in the same direction occurs when the cable sample is connected to the dynamometer wattmeter. With ordinary guard ring construction, the capacitance from sheath to ground is usually smaller than that from low plate to ground of the air capacitor; thus, it tends to reduce the total error. Special tests must be watched carefully to see that this capacitance does not exceed reasonable values, say twice that from low plate to ground of the air capacitor.

EFFECT OF HUMIDITY ON AN AIR CAPACITOR

Observation of the performance of several high-voltage air capacitors used for dielectric power-loss measurement shows occasional conflicting results on damp summer days. These cases of suspected error, although infrequent, make all dielectric power-loss measurements in terms of an air capacitor subject to doubt until the conditions associated with them can be stated. An examination of the technical literature

fails to show that such doubtful readings have been ascribed to actual power loss in very humid air, but in each such case, humidity probably varied to a greater extent than did other conditions. Hence, it seemed well to investigate the effect of humidity on an air

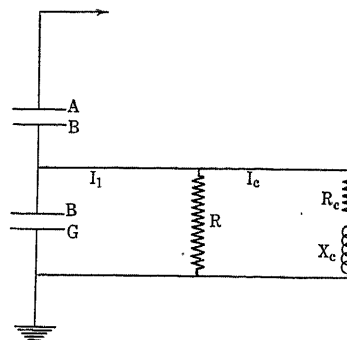


FIG. 6—EQUIVALENT CIRCUIT, AIR CAPACITOR, AND INSTRUMENT

capacitor used for phase-angle compensation of the dynamometer wattmeter for dielectric power-loss measurement.

While the comparison of heating measurements were under way, such an air capacitor, as described in detail elsewhere, was enclosed in a tight box equipped with means for controlling and measuring humidity. Humidity was increased by slowly introducing water vapor into a circulating air stream within the box or decreased by exposing calcium chloride in the box. Measurement was by wet and dry bulb thermometer in the air stream. In each case, time was allowed for the humidity of the air between the capacitor plates to assume a steady-state value.

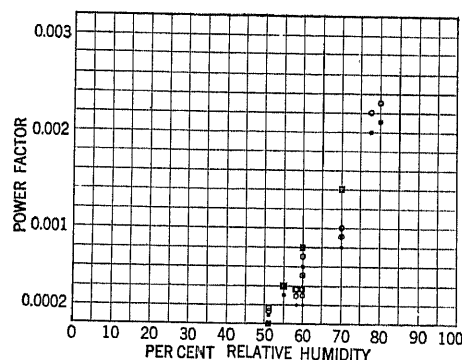


FIG. 7—POWER FACTOR OF AIR CAPACITOR AS A FUNCTION OF RELATIVE HUMIDITY

- 50 kv. 60 cycles applied
- 70 kv. 60 cycles applied
- 90 kv. 60 cycles applied
- Air temperature 25 deg. cent.

The capacitor was used at various relative humidities and temperatures to compensate the dynamometer wattmeter for measurement of the apparent dielectric power loss and power factor of the cables previously standardized by comparison of heating. The power factor of either of these cables as measured repeatedly by dynamometer wattmeter with the air in the capaci-

TABLE III
DIELECTRIC POWER LOSS IN CABLE BY COMPARISON OF HEATING, COMPARED WITH DYNAMOMETER
WATTMETER MEASUREMENT

Ohmic loss in conductor watts per cm.	Sheath temperature difference θ , deg. cent.		Voltage applied to:		Dielectric power loss.		Watts per cm.	*Power factor	
					By comparison of heating		By dyn.	By comparison of heating	By dyn.
	Th.	R. T. D							
	by th.	by R. T. D.	Cable	Kv.	Th.	R. T. D	By dyn.	By dyn.	By dyn.
0.0155	0.096	0.117	<i>B</i>	75	0.0142	0.0142	0 0154	0.0031 ₃	0.0034 ₁
0.0144	-0.008	0.021	<i>A</i>	75	0.0142	0.0143	0 0152	0.0031 ₄	0.0033 ₅
0.0182	-0.041	-0.002	<i>A</i>	82.5	0.0174	0 0177	0 0180	0 0031 ₅	0 0032 ₂
0.0182	0.068	0.104	<i>B</i>	82.5	0.0174	0 0171	0 0189	0 0031 ₆	0.0033 ₉
0.0211	0.028	0.062	<i>B</i>	90	0.0209	0.0207	0 0226	0.0031 ₅	0 0034 ₂
0.0211	-0.003	0.028	<i>A</i>	90	0.0209	0.0211	0 0215	0 0031 ₈	0.0032 ₅

*Charging current 0.0605, 0.0667, and 0.0732 milliamperes per cm. at 75, 82.5, and 90 kv respectively.

tor dry was assumed constant. (See Table III and Fig. 4). The difference between the assumed constant power factor and that measured when a given humidity and temperature existed in the air between the capacitor plates was taken as the "power factor" of the air capacitor at that humidity and temperature, indicating an actual power loss between the plates of the capacitor. Results of such measurements are shown plotted on

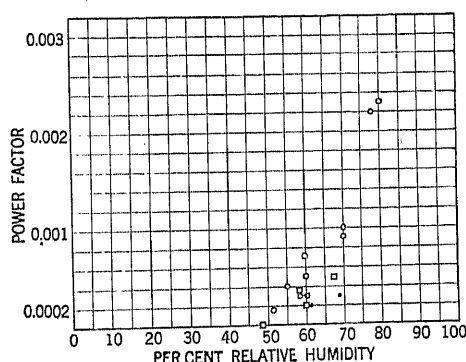


FIG. 8—POWER FACTOR OF AIR CAPACITOR AS A FUNCTION OF RELATIVE HUMIDITY

- Air temperature, 20 deg. cent.
 - Air temperature, 25 deg. cent.
 - Air temperature, 32 deg. cent.
- 70 kv. 60 cycles applied to the capacitor

Figs. 7 and 8. Considering the nature of the measurements involved, it is felt that these results are sufficiently consistent to warrant the conclusion that the capacitor is practically without loss below 50 per cent relative humidity, and shows a very marked power loss above 50 per cent relative humidity, larger at greater humidities.

Incidentally, it may be recorded that at high relative humidities, say 70 per cent or 80 per cent, flashover of the capacitor may occur at very low values, as low as 0.7 normal flashover voltage.

No explanation is offered for the observed phenomena beyond a guess concerning charge carried on dust particles. A mixture of permanent gas and unsaturated water vapor was expected to behave as a permanent gas in an electric field. It is believed that the only difference between such a mixture and the dielectric in the capacitor is the probable presence of dust in the capacitor.

CONCLUSIONS

It is believed that dielectric power loss along two 10-ft. lengths of cable, as arranged for dielectric power-loss measurement in the usual way, has been measured by a thermal method with the accuracy expected from the apparatus employed; *i. e.*, with a probable error not over two per cent. This measurement is at a power factor near 0.003. That the usual electrical measurement of dielectric power loss indicates slightly higher losses, the difference being of the order of magnitude of dynamometer wattmeter reading error, may be either accidental or associated with a small loss concentrated at the end of the measured length, in the $\frac{3}{8}$ -in. spacing between the measuring section and the guard sections, indicated on the dynamometer wattmeter but missed by the thermal scheme. In either case, it is considered that negligible loss in the air capacitor used with the dynamometer wattmeter is demonstrated, provided that care is taken to keep the relative humidity below 50 per cent in the capacitor. Present practise with this capacitor is the maintenance of relative humidity below 40 per cent.

The thermal method used seems sufficiently simple, accurate, and independent of usual dielectric power-loss measurements, that its occasional use as a check in any laboratory making careful measurements of dielectric power loss is warranted.

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Discussion

For discussion of this paper see page 836.

Residual Air and Moisture in Impregnated Paper Insulation—II

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Synopsis.—The paper describes further experiments on the drying and impregnating processes of impregnated paper insulation for high-voltage cables. Conclusions are reached as to the relative advantages of drying at atmospheric pressure and under vacuum. The qualities of the product are discussed from the standpoint of conductivity, dielectric absorption, and power factor.

The influence of electric stress on impregnated paper and the progressive change in power factor under stress are studied in accelerated overvoltage tests. Evidence is presented as to the nature of certain interesting types of progressive change of power factor in their relation to the amount of residual air.

* * * * *

INTRODUCTION

IN an earlier paper⁴ we have described a series of studies of the influence of residual air and moisture in impregnated paper insulation, such as used in high-voltage cables. Briefly, the method used was to prepare samples in groups of three, to dry them in accordance with a standard program, to impregnate them at different values of absolute air pressure, and to study the resulting influence on the power factor-voltage curves. This gave information as to the influence of residual air. Separate studies were made of the dielectric absorption and residual conductivity of the paper before and after impregnation for different states of initial dryness. These studies, in conjunction with the resulting power factor-voltage curves, gave information as to the influence of moisture.

One of the conspicuous results of these studies was the relatively small importance of the air pressure, at which impregnation took place, on the resulting power factor-voltage curves. Between one and ten cm. Hg., absolute pressure of evacuation, there was little or no change in the shape of these curves. Moreover they were exceptionally good as compared with the curves of commercial cables, being perfectly flat, up to 300 volts per mil working stress, and for temperatures up to 50 deg. cent. It is only at impregnating pressures above 25 cm. Hg. that the typical rising break in the power factor-voltage curve begins to be evident.

Another result of interest is the relatively small importance of a variation in the moisture content on the shape of the power-factor curve. Moisture content is a relative term, and the foregoing statement refers to variation as regards moisture in a condition which must be described as fairly dry.

COMPARISON OF DRYING PROCESSES

In view of these results it appeared desirable to study

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4. TRANS. A. I. E. E., Vol. 47, No. 1, 1928, p. 314.

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the relative importance of the different drying processes. The inspection of many factories in this country and abroad has shown an extremely wide variation in practise in this regard. The extremes noted were a preliminary drying process at atmospheric pressure, followed by six days under temperature and vacuum, on the one hand, and absence of all preliminary drying, immediate submersion in compound, and 24 hr. heating at reduced pressure on the other. It is obvious, therefore, that either some cables are much better than others, or that some manufacturers are wasting time and energy. The following studies were undertaken in the hopes of throwing some light on these questions.

Each test sample consisted of brass tube 2.54 cm. (1 in.) in diameter, and 121.9 cm. (4 ft.) long. The wood-pulp paper was wrapped on the tubes spirally in the usual manner to a depth of 25 layers. The finished sample was equipped with a central measuring electrode with guard electrode at each side. An electrically heated drying box, through which a slow draft of air is passed, permits drying at atmospheric pressure, and an electrically heated impregnating chamber permits an evacuation down to one mm. Hg., absolute air pressure, before the admission of the compound.

An electrically heated high-voltage test box with suitable electrostatic screening permits measurement of power factor and other alternating quantities, by means of the Schering bridge, up to stresses in the neighborhood of 300 volts per mil. Provision was also made for measuring dielectric absorption and conductivity up to 1500 volts at all stages of the several processes. For further details the earlier paper should be consulted.

In studies of this character it is important to know as closely as possible the state of the paper at the start and at all subsequent times. In drying by elevation of temperature at atmospheric pressure the final steady state of the paper depends on the temperature, the time, and the relative humidity of the atmosphere. Similar samples carried through the same drying process, but at different times, may have widely different residual moisture and electrical properties. It is obvious, therefore, that a standard temperature-

time program of drying will not result in uniform condition and properties for all samples.

Results presented in the earlier paper trace the behavior of cable paper as regards dielectric absorption and final conductivity, from the initial state when it contains about 10 per cent of moisture by weight, through a drying program which indicates clearly that for temperatures above 90 deg. cent. the conductivity, the dielectric absorption, and the power loss all increase with moisture content. C. Lubben⁵ has shown an

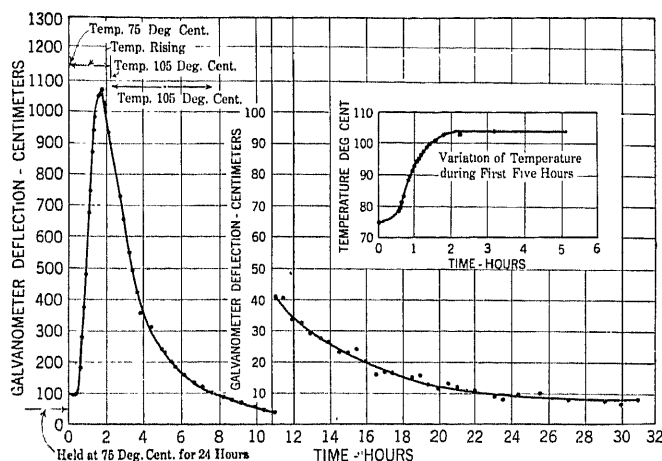


FIG. 1.—TYPICAL DRYING CURVE OF UNIMPREGNATED PAPER
Variation of conductivity with time drying in presence of slow draft of air

approximately uniform increase of dielectric absorption with moisture content up to about 5 per cent of moisture. The determination of the absolute amount of water in cable paper is difficult if not impossible, as it continues to give off moisture with increasing temperature, up to destruction. We have preferred therefore to use the conductivity of the paper as an indication of its condition as regards moisture content. The adoption of final conductivity as a standard for the condition of the paper had the advantage that it is a relatively simple matter to adjust the conductivity and hence the relative moisture content to any desired value.

As a standard condition for the paper we have taken the conductivity which results from a treatment of 105 deg. cent. for 72 hr. at atmospheric pressure in a drying box, through which there is a slow passage of air. In this process the paper reaches a steady state at the end of 48 hr. The change in the conductivity starting from the value of 75 deg. is shown in Fig. 1. The absorption characteristics are shown in Fig. 2. The final conductivity is 0.77×10^{-10} mhos per cu. cm. The paper in this condition, therefore, is seen to be an excellent insulator, although possessing high dielectric absorption.

This program of drying and the resulting conditions as described represent the state of best preliminary condition of the paper found in any of our experiments. The current from the test electrode due to the above conductivity, and at 1500 volts, gives a deflection of

3 cm. on a precision galvanometer of sensitivity 2.23×10^{-10} amperes. In what follows we shall use the galvanometer deflection directly as a measure of conductivity and moisture content.

In our studies of the relative importance of different periods of initial drying and impregnation, test samples were prepared in groups of three each, with final conductivities in the neighborhood of 30 cm., 60 cm., and 120 cm. galvanometer deflection respectively. The three samples in each group usually differ somewhat amongst themselves and it is therefore not possible to bring all three to the same value of conductivity. We have considered each group of three samples as a unit, treating and drying them together so that the final average values of conductivity are close to the figures mentioned. Specimens having the above characteristics were subjected in turn to evacuation processes represented by 5 cm., 2 cm., 1 cm., and 2 mm. Hg. absolute pressure. Throughout this program the final conductivity at the end of 24 hr. was in general taken as a basis of comparison. Three other groups were also included in this program of tests. No one of these received any preliminary drying and all therefore contained in the neighborhood of eight per cent to ten per cent of moisture. Two of these groups Nos. 28 and 29 were placed immediately in the evacuating chamber and the pressure reduced to 2 mm. Hg., the temperature being held at 105 deg. cent. and the conductivities observed at the end of 12 and 24 hr., respectively. The third group No. 36 was placed immediately in the impregnating chamber, without preliminary drying and the chamber immediately filled with compound. The pressure was reduced to 3 mm.

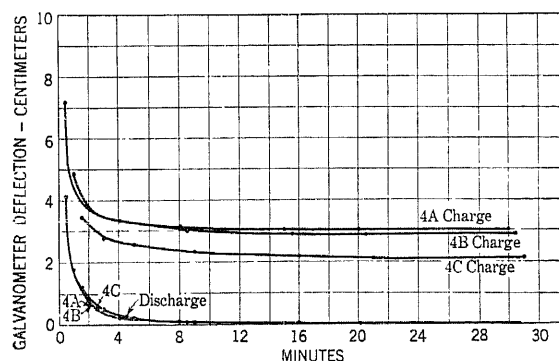


FIG. 2—CHARGE AND DISCHARGE CURVES

Cable paper specimens 4A, 4B, 4C. 1500 volts, 110.6 deg. cent., not impregnated.

Hg. and the temperature adjusted to 105 deg. cent. and both maintained constant for 24 hr.

Some of the results of these tests are given in Table I. The first column contains the numbers of the groups, each of three specimens. When the same number appears more than once it indicates a continuous run on this group, with observations at the intervals indicated in column 5. Column 2 gives the pressure of

5. Arch. Elec. 10, 1922, p. 283.

TABLE I
EFFECT UPON CONDUCTIVITY OF COMBINED DRYING AND EVACUATION
All Specimens Dried for 24 Hr. at 105 Deg. Cent. in Air before Evacuating
Conductivity Measurements at 1500 Volts D-c. and 105 Deg. Cent.

Set No	Evacuation Press. Hg.	Conductivity at Start		Reduced to Conductivity of		
		Limits	Average of 3 Spec.	Time Interval in Hr.	Limits	Average of 3 Spec.
27	2 mm.	79.00-179.00 cm.	132.00 cm.	24	2.45- 4.10	3.38 cm.
26		9.50- 10.50	10.00	24	2.95- 3.45	3.20
22		3.80- 8.15	5.72	24	.50- 5.00	2.36
27		2.45- 4.10	3.38	36	1.35- 2.25	1.88
21	1 cm.	95.00-136.00	119.00	23	7.97-10.57	9.15
25		48.00-125.00	80.60	23	8.20-12.75	9.72
26		25.00- 57.50	38.60	24	10.80-13.00	12.25
22		12.60- 17.80	16.30	24	6.25-12.05	8.85
26		10.80- 13.00	12.25	24	9.50-10.50	10.00
25		8.20- 12.75	9.72	24	8.20-13.20	9.93
21		7.97- 10.57	9.15	23	7.65-10.10	8.78
21		7.65- 10.10	8.78	23	6.75- 9.25	7.90
24	5 cm.	65.00-144.50	105.50	23	15.02-18.77	16.64
23		49.00- 78.00	65.80	25	8.15-11.05	9.57
22		32.50- 34.50	33.50	24	12.00-16.65	15.00
24		15.02- 18.77	16.64	24	11.95-13.70	12.88
24		11.65- 13.25	15.76	48	9.75-13.00	11.85
22		12.00- 16.65	15.00	24	12.60-17.80	16.30
24		11.95- 13.70	12.88	23	11.65-13.25	15.76
23		8.15- 11.05	9.57	20	7.95-11.15	9.58
No Preliminary Drying						
28	3 mm.	Wet		12	3.00- 3.65	3.33
		3.00- 3.65	3.33	12	1.75- 2.85	2.30
29	3 mm.	Wet		12	2.70- 3.85	3.20
		2.70- 3.85	3.20	12	1.80- 2.35	2.08

evacuation; column 3 the conductivity in cm. galvanometer deflection, the two figures indicating the extremes in the three samples of the respective group; and column 4 the average value of conductivity of the

and 29, shown at the bottom of the table, receive no preliminary drying and were placed immediately in the evacuating chamber and the pressure reduced to 3 mm. No measurement was made of their initial conductivity and their initial state is described simply as "wet." Group No. 36 was placed in the impregnating compound without any preliminary drying or evacuation. The figures for the initial and final conductivity therefore have no significance in relation to the figures given in Table I. The properties of this group are best understood by a consideration of the power factor-voltage curves. These are shown in Fig. 3 and discussed in a later paragraph.

The results as given in Table I indicate that for samples having different values of initial conductivity, corresponding to 30, 60, and 120 cm. galvanometer deflection at 1500 volts, when subjected to 105 deg. cent. and vacua represented by 5 cm., 2 cm., and 1 cm. Hg., absolute air pressure, it is not possible under any length of time to reach the same degree of dryness represented by a sample heated for 48 hr. in a slow draft of air at the same temperature and at atmospheric pressure. The standard value of final conductivity referred to above is approached more and more closely, however, the lower the evacuating pressure.

Evacuation pressures in the neighborhood of 2 or 3 mm. Hg. are necessary if the sample is to be brought down to the standard value of conductivity. Moreover at this pressure and 105 deg. cent. temperature this final conductivity may be reached in 24 hr. regard-

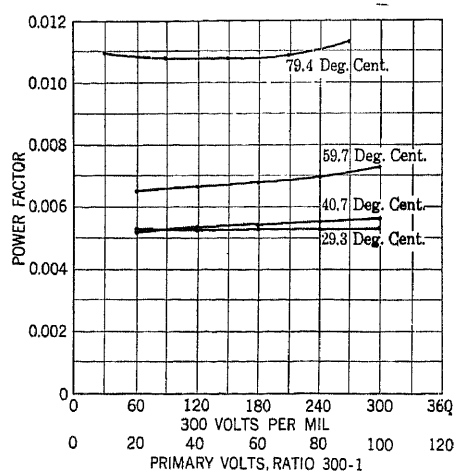


FIG. 3—POWER FACTOR—VOLTAGE CURVES

Specimens 36A, 36B, 36C. Conductor diameter = 1.0 in. Insulation = 0.10 in. wall. No preliminary drying

group. Column 5 gives the duration of exposure to the vacuum and column 6 and 7 the conductivities at the ends of the intervals given on column 5. The general arrangement of the table is such as to show continually decreasing values of initial conductivity as shown in column 4, at each pressure of evacuation. Groups 28

less of the initial state of the specimen; *i. e.*, a specimen that has had no preliminary drying, and contains therefore in the neighborhood of ten per cent of moisture, may be completely dried in 24 hr. at 2 mm. Hg. and 105 deg. cent. (sets Nos. 28 and 29). Special provision should be made in this case, however, for taking care of the large amount of moisture liberated in the evacuating system.

A freshly prepared sample (group No. 36) having no preliminary drying placed immediately into the impregnating compound at temperature 105 deg. cent. and pressure reduced to 3 mm. Hg. and maintained for a total duration of 24 hr., yields surprisingly good results. The power factor-voltage runs were made on such a series of samples at temperatures 29 deg., 40 deg., 59 deg., and 79 deg. cent. The curves are shown in Fig. 3. The curve at 29 deg. cent. is perfectly flat up to 300 volts per mil, thus showing a curve which compares favorably with our best specimens obtained by other methods of drying and impregnation. With increasing temperature the power factor-voltage curve shows only a slight tendency to rise over the voltage range. This is at variance with the behavior of our best specimens, which with increasing temperature show power factor-voltage curves with a maximum at relatively low stress and thereafter decreasing values of power factor. See Fig. 4. This effect is entirely

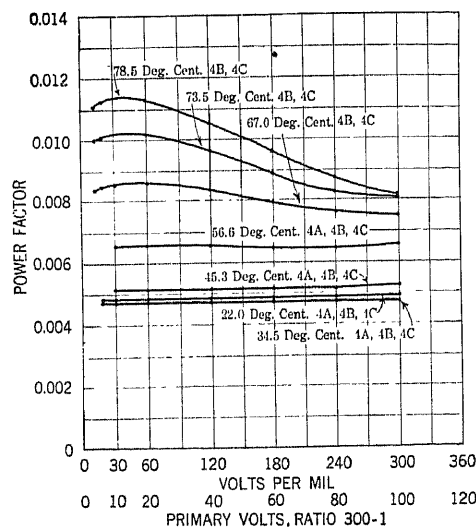


FIG. 4—POWER FACTOR—VOLTAGE CURVES

Specimens 4A, 4B, 4C in parallel. Conductor diameter = 1 in. Insulation = 0.10 in. wall. Impregnated at 2 mm. pressure. Conductivity in dried state = 4A—3.40 cm.; 4B—3.45 cm.; 4C—2.55 cm.

absent even at 79 deg. cent., in the specimen now under consideration, the power factor-voltage curve at that temperature being approximately flat at low stresses, rising somewhat toward higher stresses. On the whole, however, the curves of set No. 36 show no marked internal ionization and compare well with well dried specimens. The absorption curves taken at 1500 volts continuous potential showed no marked differences.

It is interesting to speculate as to an explanation of the differences between the curves of Figs. 3 and 4. In the foregoing paper we have traced the intimate relation which exists in impregnated paper between the dielectric loss and the dielectric absorption, as observed under continuous potentials. Moreover, there is much evidence and we are convinced that the phenomenon of dielectric absorption, not only in impregnated paper, but in many other forms of insulation, arises in the conductivity, in the case of paper of the impregnating

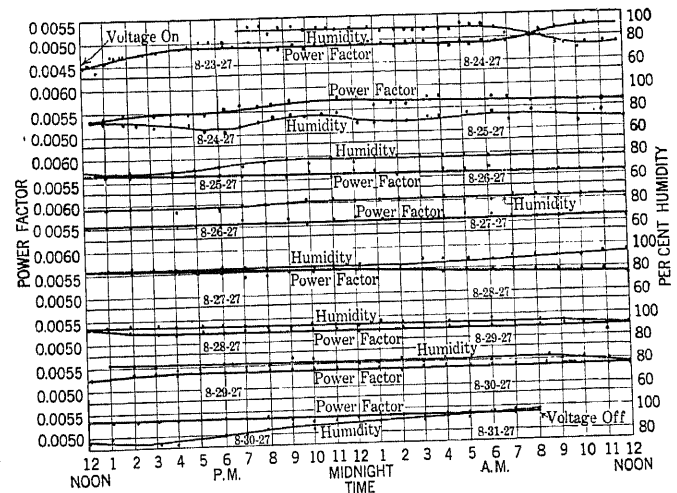


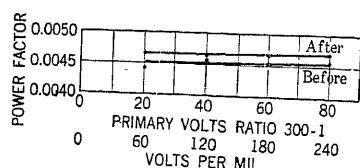
FIG. 5—VARIATION OF POWER FACTOR WITH TIME

Cable specimens 33A, 33B, 33C in parallel. With 12,000 volts, a-c., 60 cycles applied continuously—40 deg. cent.

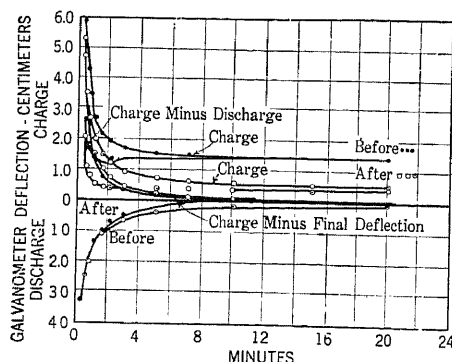
compound, and in other materials in local paths, due to moisture or other impurities. Now the conductivity of the best grades of insulating liquids is due to the presence of mobile ions in limited numbers. These ions may be swept out at relatively low voltage acting for long periods of time, and more rapidly at higher voltages. In the case of the best impregnated paper, as illustrated in Fig. 4, we may therefore explain the decrease in power factor with increasing potential gradient at the higher temperatures as follows: At the higher temperatures the ions are more mobile and with increasing voltage gradient they are swept out of the field more and more rapidly with consequent reduction in conductivity. At the same time the out-of-phase or charging component of the current increases with the potential gradient, the two effects combining to cause a falling value of power factor with increasing potential gradient. In the case of the curves shown in Fig. 4 relatively moist paper is immediately immersed in the compound. The drying and evacuating under compound leaves some of the moisture in the oil. This has the effect of greatly increasing the number of ions present in the oil and probably in slowing up their mobility. The result is, that with increasing potential gradient conductivity and capacity remain approximately constant, resulting in an almost flat power-factor curve.

It is interesting to note that at low temperatures these

samples which were dried and impregnated at the same time and with a total time duration of only 24 hr., show power-factor curves comparing very favorably with those of samples, dried, evacuated, and impregnated in separate stages over considerably longer periods of time. At the higher temperatures values of power factor reached are not seriously high. This raises the question whether this short and convenient method of drying results in a poor cable. There is undoubtedly an indication of danger in the rising power factor-voltage curve at higher temperatures. Thoroughly dried and evacuated insulation shows a markedly drooping curve. We attribute the rising curve in the



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts for 190 hr., 60 cycles, —24.2 deg. cent.



Charge and discharge curves, 1500 volts d-c. Before and after specimens were held at 12,000 volts for 190 hr., 60 cycles, —24.2 deg. cent.

FIG. 6—SPECIMENS 33A, 33B, 33C IN PARALLEL. EVACUATED AND IMPREGNATED AT 2 MM.

present case to a greatly increased conductivity of the compound, due to moisture. Life tests now in preparation may bring out serious results of these differences.

CHANGE OF POWER FACTOR WITH TIME

Those accustomed to measuring the power factor of cables and impregnated paper in general have frequently noted that the power factor changes with the time. For the most part, these reported changes are gradual but in a few cases very rapid changes have been reported, as for example, an absolute change of 40 per cent within a few minutes. In our own experiments we have noted changes of a few per cent in observed values from day to day, but for the most part they have not been sufficiently great to require special study nor to affect the general conclusions we have drawn from our studies. The most serious changes of this type we have noted are associated with poorly impregnated specimens at high temperatures. In these cases ascending and descending power factor-voltage curves

are separated and variations with time have been noted. Following are the results of further studies in this direction:

One group of samples (No. 33) was dried at 105 deg. cent. and an absolute pressure of 2 mm. Hg. for 24 hr. and then impregnated at approximately this pressure. Power factor-voltage curves were then taken at room temperature (see Fig. 6) and then the temperature was raised to 40 deg. cent. and held constant. The power factor-voltage curve was again taken and all specimens were short circuited and grounded for four hr. The samples were then subjected to 12,000 volts, corresponding to a gradient of 120 volts per mil, continuously for 190 hr. The variation of the power factor during that interval is shown on the accompanying curve No. 5, which shows also the variation of the relative humidity. The value of power factor could be read at intervals as short as two min. When the values were changing frequent observations were made, and always at intervals of at least one hr. It will be noted that during the entire run the maximum variation in power factor was from 0.0045 at the start to 0.0057 on the night of August 24. The final steady value of power factor was 0.0052. The greater part of this difference arises in the first four hr. after the application of voltage, the value reached at this period being 0.0049. The total change during the whole run succeeding this was therefore seen to be relatively small, *i. e.*, 0.0049 to 0.0052.

There was some suggestion that the rise of power factor on the 24th and its gradual fall on the 28th was due to the influence of the relative humidity on the constants of the air condenser of the Schering bridge. If an increase of relative humidity of the atmosphere caused an increase in the phase difference of the air condenser, by leakage or otherwise, as has been suggested, the influence on the Schering bridge would be to lower the observed value of power factor of the specimen. Such an effect would cause the changes indicated in the two days mentioned and as shown on curve No. 5. On the other hand on the 30th and 31st there was a steady increase in the relative humidity without apparent effect on power factor.

In order to test the value of the above mentioned assumption, as to the influence of relative humidity, we made a few preliminary experiments on a small enclosed air condenser in which the humidity of the atmosphere could be controlled. We found that above 80 per cent relative humidity there was an effect of the type mentioned; namely, the conductivity and so the phase difference of the air condenser increased to a value other than zero. Experiments are still in progress to see whether this effect is due to a leakage over the insulation or to some other cause. In the meantime the results obtained have enabled us to correct the few power factor readings which we have found it necessary to take at values of relative humidity above 80 per cent.

At the end of the above mentioned run on group

No. 33, the voltage was interrupted for intervals of one min., five min., and for 30 min., and the power factor measured at the end of each interval. No change in power factor from value 0.0052, at which the original run ended, was observed. In a 20 hr. period without voltage, however, there was a recovery in power factor from 0.00510 to 0.00477. All of these measurements were at temperature of 40 deg. cent. The temperature was then allowed to fall and another power factor-voltage curve taken at room temperature, see Fig. 6. This checked very closely with the original observations indicating that the several series of voltage cycles, the

also gives the curve of changes in relative humidity. It will be noted that there was no abnormal change in power factor. In fact, the power factor remains remarkably constant, beginning and ending at the same value 0.0047, and with a maximum elevation in the intervening period to 0.00495. There is, however, an elevation in the relative humidity above 90 per cent towards the end of the run. Making the corrections on the observed value of power factor in the manner already referred to, the final value of the power factor becomes 0.00495, as indicated in Fig. 8. We therefore found in this group of specimens, as also in group No. 33, a slight increase in the value of power factor as a result of the time run under voltage. There is therefore no evidence here of any marked differences between the specimens impregnated at 2 mm. and at 15 cm. The power factor-voltage curves compared with those for similar specimens reported in the earlier paper are much the same as to both type and values.

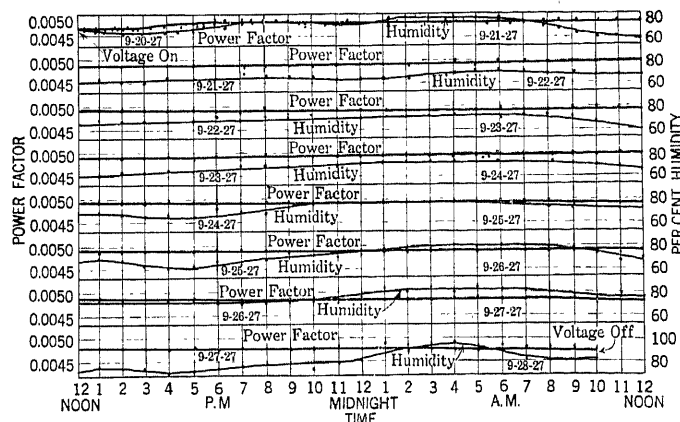


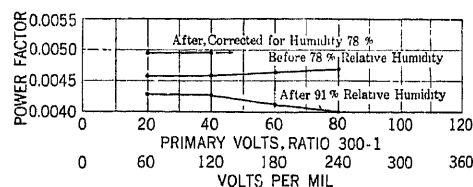
FIG. 7—VARIATION OF POWER FACTOR WITH TIME

Cable specimens 34A, 34B, 34C in parallel with 12,000 volts, a-c., 60 cycles applied continuously—40 deg. cent.

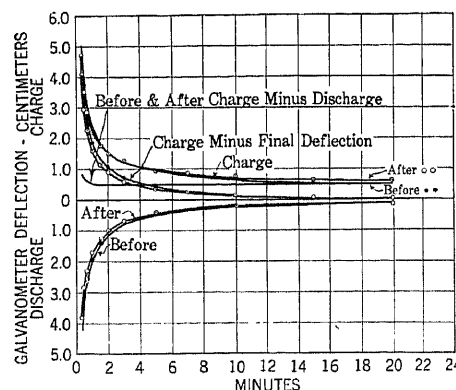
sustained run at 120 volts per mil, and the successive interruptions have not affected the insulation in any permanent way. We conclude from these observations that with well impregnated insulation no sharp and no permanent changes in power factor are to be looked for within a voltage run of 190 hr. at 120 volts per mil.

Measurements were also made of the dielectric absorption and final conductivity at 1500 volts and at atmospheric pressure, before and after the time run described above. The results of these tests are shown in Fig. 6. An interesting feature in these curves is that there was a slight increase in the absorption and a very large decrease (about 60 per cent) in the final conductivity. There is no apparent explanation for this decrease in conductivity. We have noticed this effect in connection with other specimens and it seems to be associated with an initial and temporary condition of the oil following impregnation. It has no apparent influence on power factor observations, as these are determined in large measure by the absorption.

Similar studies as those described for group No. 33 were made with group No. 34, which were dried and evacuated at 2 mm. pressure, but impregnated at 15 cm. pressure. The purpose here was to study the possible influence of a greater proportion of residual air in causing time changes of power factor. The 190 hr. run at 120 volts per mil is shown in Fig. 7, which



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40.3 deg. cent.



Charge and discharge curves, 1500 volts, d-c. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40.2 deg. cent.

FIG. 8—SPECIMENS 34A, 34B, 34C IN PARALLEL. EVACUATED AT 3 MM.—IMPREGNATED AT 15 CM.

The absorption showed no marked changes following the 190 hr. run (see Fig. 8).

Group No. 35 was dried and evacuated at 2 mm. pressure and impregnated at 30 cm. pressure. Impregnation at this pressure was known to result in a rising power factor-voltage curve. This group was subjected to the same type of run of 190 hr., at 120 volts per mil and at 40 deg. cent. The results in the power factor are indicated in Fig. 9, which again shows an initial period with rise from 0.0056 to 0.0058 over the first hour and thereafter a slow decrease to a very uniform and steady condition, the testing ending with

the value 0.0053, slightly below that at which it started. There were no abnormal elevations of humidity as indicated by the humidity curve, also plotted in Fig. 9.

Of particular interest, however, in connection with

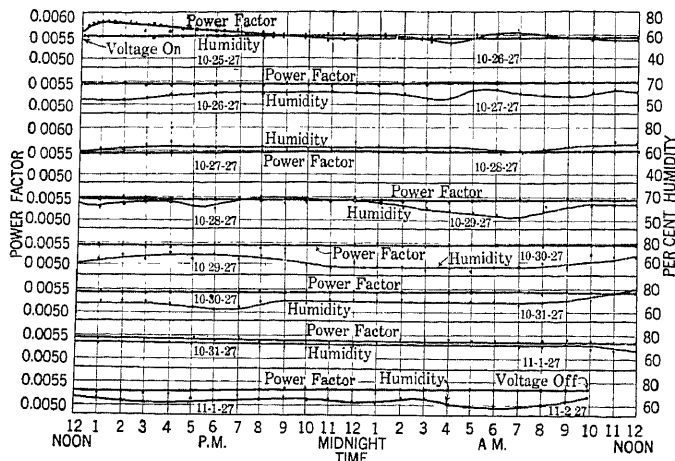
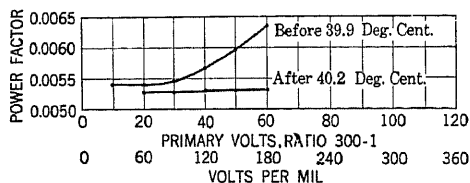


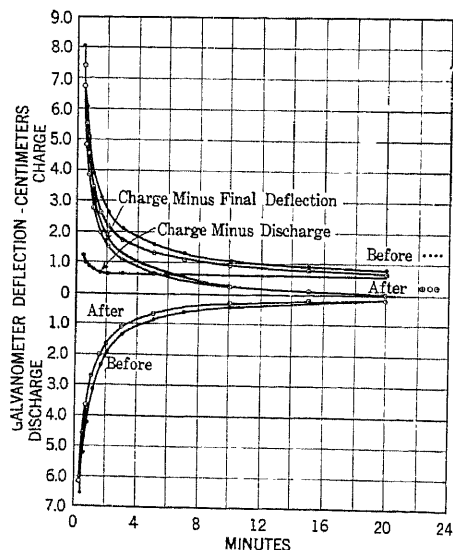
FIG. 9—VARIATION OF POWER FACTOR WITH TIME

Cable specimens 35A, 35B, 35C in parallel with 12,000 volts, a-c., 60 cycles applied continuously

group No. 35 is the marked change in the power factor-voltage curve between the beginning and the end of this time run. These curves are shown in Fig. 10, and it



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—39.9–40.2 deg. cent.



Charge and discharge curves, 1500 volts, d-c. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—deg. cent.

FIG. 10—SPECIMENS 35A, 35B, 35C IN PARALLEL. EVACUATED AT 3 MM. IMPREGNATED AT 30 CM.

will be seen that at the beginning there is evidence of pronounced internal ionization, which however seems to disappear as the result of prolonged application of voltage. In the same figure will be found the absorption curves for the beginning and end of the test, indicating a decrease of absorption corresponding to the decreases observed in power factor.

Two principal explanations suggest themselves for the improvement in the ionization curve of group No. 35 just described. The first of these is a possible improvement in the impregnation due to the fact that in the time runs the specimens are immersed in the compound in which they are impregnated. Although at ordinary

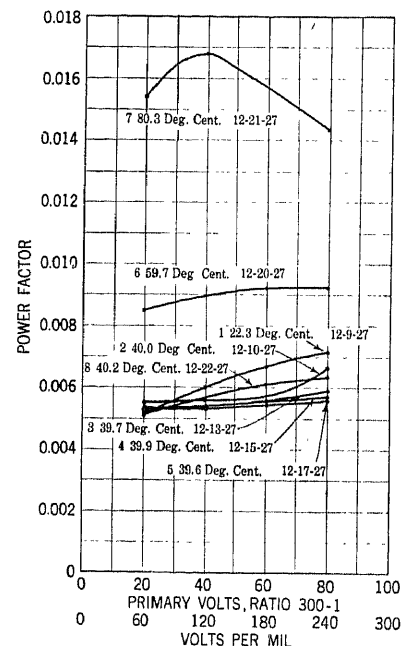


FIG. 11—SPECIMENS 37A, 37B, 37C

Impregnated at 30 cm. Hg. with dried influence of submersion in compound. Curves taken in order 1-8 on dates shown. Voltage applied only during measurements

temperature and up to 50 deg. this compound is fairly stiff and does not flow readily, it appears possible that there may be a slow change in the degree of impregnation of the samples, over so long a time as 200 hr. The other possible explanation is an influence of the continued application of voltage.

In order to test the relative importance of these two suggestions an additional group of specimens, group No. 37, was dried and impregnated at 30 cm., giving a group in all respects similar to group No. 35. After the usual process of impregnation, the power factor-voltage curve was taken at atmospheric temperature. The resulting curve is shown as No. 1 in Fig. 11. We then raised the temperature to 40 deg. cent. and power factor-voltage curve No. 2 in Fig. 11 was observed. Voltage was then removed from the specimens and they were allowed to stand in the compound at 40 deg. cent. for a period of 190 hr., voltage being applied only long enough to obtain the power-factor curves Nos. 3, 4, and 5 of Fig. 11. It will be noted therefore that there

was an apparent steady improvement in the direction of flattening of the power-factor curve, during this period. At the end of the period, however, the specimens were taken through a temperature cycle up to 80 deg. and on returning to 40 deg. it was seen that the power-factor curve again takes on the ascending shape approximating that of the initial condition. We conclude from these observations that while there is some evidence of improvement of the insulation when stand-

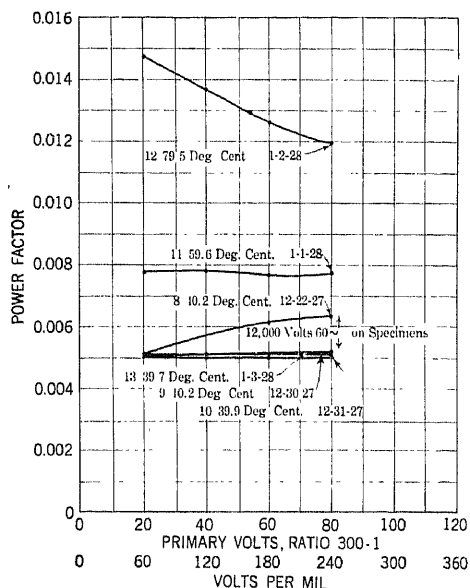


FIG. 12—SPECIMENS 37A, 37B, 37C

Impregnated at 30 cm. Hg. well dried. Influence of continuous application of voltage. Curves taken in order 8-13 on dates shown. 12,000 volts, 60 cycles on specimens for 190 hr. between curves 8-9, at other times voltage on only during measurements

ing idle in the compound, it is not a permanent improvement and that after an elevation of temperature the insulation again takes on its original undesirable characteristics.

In order to study the influence of the prolonged application of voltage, the same set of samples, No. 37, was next subjected to a run of 190 hr. at 120 volts per mil, at a temperature of 40 deg. cent. The results are shown in Fig. 12, in which curve No. 8 of Fig. 11 is repeated, and the succeeding curves numbered in the order in which they were taken. It will be noted that the 190 hr. run results in a greatly improved, that is, a perfectly horizontal power-factor curve at the end of the run, that a succeeding temperature cycle gives power-factor curves at higher temperatures, similar to those of well impregnated samples, although perhaps a little higher, and that on return to the original temperature of 40 deg. cent. the power-factor curve retains its horizontal position.

The results of the foregoing tests are quite surprising. Although the samples were thoroughly dried they were impregnated at a pressure of 30 cm. Hg. and under these conditions tests, within a period shortly after preparation of specimens, have indicated very unde-

sirable characteristics from the standpoint of ionization. Apparently therefore the insulation is greatly improved by exposure for 190 hr. to a stress of 120 volts per mil. On completion of the foregoing tests all three of the specimens of group No. 37 were dismantled and the paper carefully unwound. It was found that all three of them present all the outward evidences of thorough impregnation, that is to say, the color was uniform throughout and there was entire absence of air pockets or layers. However, on unwrapping samples No. 37 it was found that the paper was noticeably drier and more crinkly than that removed from our best type of samples well impregnated at lower pressures. The paper seemed to be drier and actually to have less compound in it.

In order to test these questions still further similar runs were made on a group of samples, No. 42, which contained still more air. In the cases of all the foregoing groups, which were dried before impregnation, this drying was accomplished by subjecting them to a temperature of 105 deg. cent. and absolute pressure, 2 mm. Hg. for a period of 24 hr. They were then allowed to stand for two hr. at the air pressure at which impregnation was to take place, *e. g.*, 30 cm. Hg. in the case of group No. 37. Group No. 42 was dried at 105 deg. cent. in a slow draft of air at atmospheric pressure as already described. The final moisture

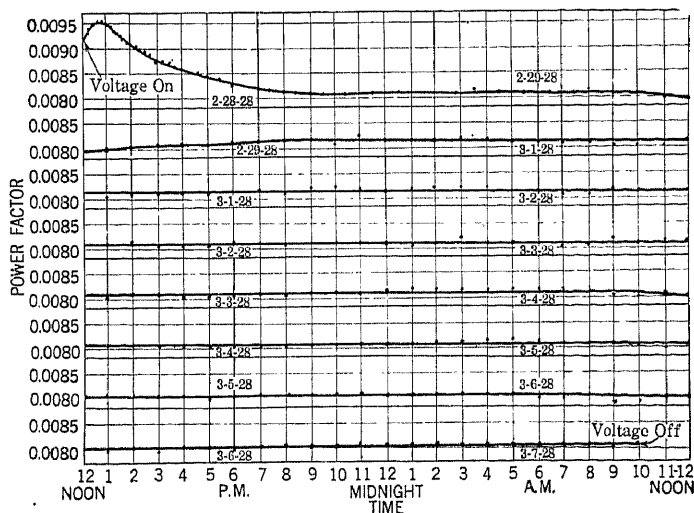
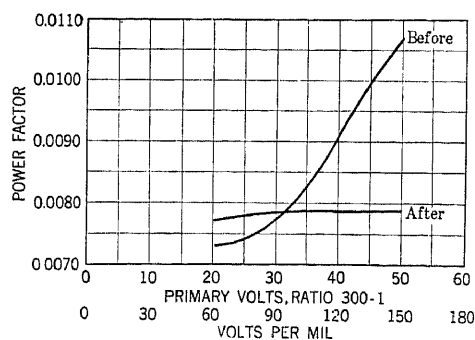


FIG. 13—VARIATION OF POWER FACTOR WITH TIME

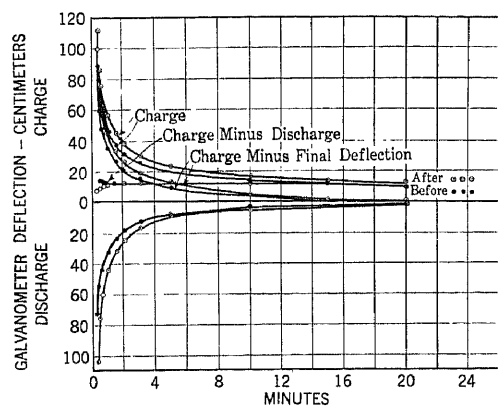
Cable specimens 42A, 42B, 42C in parallel with 12,000 volts, a-c., 60 cycles applied continuously—40 deg. cent

content as indicated by the conductivity was the same as in group No. 37. They were then impregnated at a pressure of 30 cm. This group, No. 42, was never subjected to an atmospheric pressure lower than 30 cm. It therefore contained more air than the foregoing group No. 37, although both were impregnated at the same pressure. Fig. 13 gives the result of the 190 hr. run at 120 volts per mil and Fig. 14 shows the dielectric absorption and the power factor-voltage curves, both before and after the time run, for group No. 42. The

interesting things to note about these curves are the slight initial rise of power factor at the beginning of the time run, which however, was followed by a noticeably greater decrease during the succeeding eight hr., and the marked changes of the power factor-voltage curve at the end of the time run. The changes in the dielectric absorption are in accord with the changes in power factor. Of these changes the most interesting is the marked improvement in the power factor-voltage curve, as the result of the time run. Before the run this curve rose sharply above 20 volts per mil, indicating copious internal ionization as expected, in view of the large amount of air known to be entrained in the insulation. After the time run, however, this curve became almost flat, lying slightly



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40 deg. cent



Charge and discharge curves, 1500 volts, d-c. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40 deg. cent.

FIG. 14—SPECIMENS 42A, 42B, 42C IN PARALLEL. EVACUATED AND IMPREGNATED AT 30 CM.

higher at lower voltage stresses, but rising very little over the remaining voltage range. It appears, therefore, that the improvement noted in connection with group No. 37, resulting from a prolonged run at high voltage, is still more sharply emphasized in the case of group No. 42.

We conclude, therefore, that well dried paper when impregnated at 30 cm. Hg., absolute pressure, has in its initial condition a considerable amount of air and reveals a sharply rising power factor-voltage curve indicating considerable internal ionization. In its earlier stages if left to itself there are progressive

changes in the internal condition, as to impregnation, but no permanent change in the undesirable ionization characteristic. On application of voltage there is a steady improvement in the condition of the insulation as regards its ionization characteristic, as indicated by the power factor-voltage curves, and after approximately 200 hr. the insulation reaches an apparently excellent condition with little or no evidence of internal ionization.

In explanation of the foregoing we offer the following: In the original state of the insulation the air exists for the most part in very thin layers and in the interstices of the paper. The application of the voltage ionizes these separate air pockets. The amount of oxygen in each air pocket is limited and is exhausted by the process of ionization, passing into ozone and into combination with the paper and compound. As regards the nitrogen either one of two things can occur. If it is left native, and therefore inert, we may suppose that with increasing temperature the nitrogen expands and goes into solution with the compound which has the power of absorbing gases in some quantity. A more promising alternative is that in the presence of ionization the nitrogen combines to cause nitrous oxides, and with the traces of water that may be present to form nitric acid, which would thus join the oxygen in attacking the paper. Finally these processes, singly or together would account for a disappearance of the air pockets, which are evident if specimens of this type are dismantled in the early stages of their life. The rate of decrease of this disappearance of air is indicated by the curve of Fig. 13 in which it is seen to occur during the first seven or eight hr. after the application of voltage. This explanation would also account for the relatively dry and crinkly appearance of the paper at the end of the run under high stress, and which was very evident in groups No. 37 and No. 42. We attribute this condition to the formation of small amounts of wax or other solid decomposition product which has been frequently noted in connection with over-stressed cable insulation.

The evidence of the foregoing results indicates clearly that the continued application of voltage may result in a marked improvement in the power factor characteristics of impregnated paper, through a consumption or absorption of entrained air, as a result of the process of ionization. An original ionization characteristic is not necessarily a permanent property of this type of insulation.

Another feature of interest in connection with the time runs, described above, is the initial rise in power factor during the first hour or two after the application of voltage. We attribute this rise to the energy liberated within the body of the insulation as the result of dielectric loss. The rise stops as soon as the automatic temperature control equipment readjusts itself to the new rate of energy supplied. Following this initial rise it will be noted that in the cases of samples

No. 35 and No. 42 there is a steady decrease in power factor below the initial value. This decrease is most sharply marked in group No. 42. In the case of these two samples we attribute this steady decrease to the consumption of the entrained air and a consequent lessening of the amount of ionization leading to a decrease in energy loss. The effect is more marked in the case of group No. 42, because that group was known to contain more air originally. One of the authors has already recorded⁶ experiments showing the limited amount of oxidation and the gradual change in the nature of the discharge in a thin ionized layer of air, when the layer is completely sealed.

In the earlier paper we have emphasized the close relationship between dielectric absorption and dielectric loss or power factor. The results of the present studies are quite consistent in this regard. In all cases of power-factor changes during the time runs described above, corresponding changes may be observed in the dielectric absorption. The absorption curves, however, were all taken at 1500 continuous volts, which gives a stress far below the alternating values used. Absorption curves for this type of insulation at stresses comparable in value to those of alternating service and tests, are badly needed. In connection with the absorption curves we have plotted the difference between the currents of charge and discharge. This difference shows the irreversible absorption current which is seen to have a considerable value in all the above cases and to rise sharply toward the short time interval, after the application of voltage. This indicates not only the complex character of dielectric absorption as it occurs in impregnated paper, but also that the irreversible absorption current accounts for a substantial portion of the total loss. It is our hope to be able to extend our studies in this direction in the near future.

These studies were carried out in the School of Engineering of The Johns Hopkins University at the request and with the support of the Subcommittee on Impregnated Paper Insulated Cable Research, of the National Electric Light Association, D. W. Roper, Chairman. For the continued interest and hearty cooperation of the members of the committee the authors extend their grateful acknowledgment.

CONCLUSIONS

Taken in conjunction with the earlier paper our present results would seem to indicate the following:

1. For the drying of cable paper before impregnation, preliminary drying before vacuum treatment is unnecessary, except perhaps as a convenient method of driving off a large part of the water always found in cable paper.

2. Drying at reduced air pressure is very much more rapid than drying in the open, for the same drying temperature. At a drying temperature of 105 deg. cent. at atmospheric pressure, and in a steady draft of

air, a steady condition of the paper as regards dryness is reached only after from two to three days. The same condition can be reached if dried at 105 deg. cent. in a vacuum of from two to five mm. Hg. absolute pressure, in from 12 to 24 hr. It is not possible, however, to reach this same condition of dryness over any length of time if the evacuation pressures are above 5 mm. Hg. It is probable that a continuous replacement of water vapor, by dry air in the vacuum chamber, would alter this conclusion. The great value of the draft of air, however, when drying at atmospheric pressure is evident. Higher values of the temperature result in further improvement as regards dryness and conductivity.

Initially undried and unevacuated paper placed immediately in the impregnating chamber and then subjected to heating to 105 deg. cent. and evacuation pressure of 3 mm. Hg. for 24 hr., results in an insulation having remarkably good properties. At temperatures up to 40 deg. or 50 deg. the power-factor-voltage curves are flat and of value of the same order of magnitude as those pertaining to specimens that are far more carefully dried. In the upper range of temperatures the power-factor curves have abnormal shapes, although they do not show values unduly high.

4. For thoroughly dried paper impregnated at 105 deg. cent. and pressures of 2 mm., 15 cm., and 30 cm. there are no sharp changes in power factor following abrupt changes of voltage.

5. Prolonged runs under voltage cause no appreciable changes in the properties of thoroughly dried and impregnated insulation (dried at 2 mm. Hg. and impregnated up to 15 cm. Hg.). For insulation impregnated at higher pressures there is a pronounced improvement as a result of the continued application of voltage. We attribute this to the slow consumption of the entrained air in ionization, and its combination with the compound, with resulting decrease in ionization losses.

6. The improvement in power factor noted in the foregoing paragraph is accompanied by a noticeable drying or stiffening of the paper. This we attribute to the production of solid decomposition products of the oil. We thus have the suggestion that the generation of "x-wax," or similar product, is associated with a decrease in power factor. Whether this would continue through long periods is a question for further study.

7. Poorly impregnated cable insulation may show excellent power-factor curves indicating low ionization for temperatures up to 40 deg. or 50 deg. cent. and yet not have permanent characteristics. Examples are group No. 36, impregnated without preliminary drying and showing the curves of Fig. 3, and the several curves around 40 deg. of group No. 37. In such cases a temperature cycle may result in a marked change of characteristics. At higher temperatures there are

6. J. L. A. I. E. E., December 1923, p. 1297.

often marked differences from the characteristics of insulation which is thoroughly dried and impregnated.

8. A general survey of these and foregoing studies indicates the relative unimportance of air pressure of impregnation within a fairly wide range say up to 15 cm., and even up to 30 cm., if the paper is vacuum dried. Excellent power factor-voltage curves may be found throughout this range. We conclude therefore that the sharply rising curves and rapid changes in power factor, often noticed in commercial cables are due to relatively large and extended areas of entrapped air or gases, resulting either from imperfect impregnation, distortion in handling, or temperature expansion of lead sheath.

Discussion

DIELECTRICS AND INSULATION

(SCOTT, BOUSMAN, BENEDICT, WHITEHEAD, KOUWENHOVEN, AND HAMBURGER)

BALTIMORE, MD., APRIL 17, 1928

W. F. Davidson: In the paper by Scott, Bousman, and Benedict mention is made of some tests that were conducted to determine the influence on the values obtained of controlling the potential of the guard circuits and in this particular case they found it quite satisfactory to connect the guard circuit to ground. However, in some cases this would not give satisfactory results. I think it is well to caution people working with such measurements to see that they check their own individual circuits.

As a case where serious errors were introduced, I might mention one in which we made a considerable number of measurements at voltages corresponding to a stress of about 250 to 300 volts per mil. In this case we found harmonics in the guard circuit which introduced serious errors in measurement unless they were carried off.

It would seem that the information with regard to the air-capacitor performance (Fig. 7) would be considerably more valuable if stated in terms of stress instead of total voltage applied.

Donald Bratt: The consideration of calorimetric methods in dielectric research on high-voltage lead-covered cables confronts us with several interesting problems. The temperature rise on the surface of the cable sheath due to dielectric power loss is significant not only for its average value when taken over a considerable length of cable, but also for its fluctuations over this length.

All our present electrical methods for measuring dielectric power will give only the average value. Now it is well known that a cable which ultimately fails on a high-voltage test gradually develops a "hot spot" at the place of failure long before this failure occurs. It does not seem impossible, therefore, that a study of the steady-state temperature rise whether it be due to dielectric loss alone, to copper loss alone, or to both, could be used as a measure of the *homogeneity* of the insulation.

Let us first take the case of dielectric loss. Assume that a long cable sample subject to high voltage has developed a steady surface temperature rise $\theta = f(x)$ where $f(x)$ is a temperature which may vary over the length of the cable, as measured say from its midpoint ($x = 0$). In particular, let $f(x) = \theta_1 + \theta_2 E^{-mx^2}$ meaning that in addition to the normal temperature rise θ_1 there adds an amount $\theta_2 e^{-mx^2}$ due to a typical hot spot at $x = 0$ (see Fig. 1 herewith). The question now arises: What conclusions can be drawn from such a temperature curve in regard to the specific loss? It is evident that the sheath must exercise some equalizing influence, so that the variation in losses is more pronounced than exhibited by the surface temperature. Considering the longitudinal heat conduction in the cable as well as the

heat dissipation from the cable surface, an expression involving maximum and minimum specific loss is easily derived:

$$\frac{W_{max} - W_{min}}{W_{min}} = \frac{\theta_2}{\theta_1} \left(1 + \frac{2 m \lambda a}{T S} \right)$$

W_{max} occurs at $x = 0$

W_{min} occurs at $x = \pm \infty$ (meaning *far* from $x = 0$)

T = heat dissipation constant.

S = sheath circumference

λa = longitudinal heat conductivity.

Substituting ordinary values for those constants, and assuming m to be 10^{-3} per cm^2 (this would correspond to a temperature decreasing to $\frac{1}{2}$ of its maximum value for $x = \pm 25$ cm.) we obtain

$$\frac{2 m \lambda a}{T S} = 2.5 a b t.$$

and the range of variation is seen to be $1 + 2.5 = 3.5$ times as severe as that which would be indicated by the surface temperature.

In view of the recent discussions of thermal breakdown, it would seem to be of great interest to determine the greatest value of m conformal with steady-state performance, as this maximum value undoubtedly reflects the quality of the insulation.

Considering further the question of homogeneity of insulation and the likelihood of a hot spot developing in a region of (let us say) poor heat conductivity, it might be desirable to have a factory test whereby such regions could be detected without even cutting the cable and preparing a sample. Observation of surface temperature rise when the cable is heated,

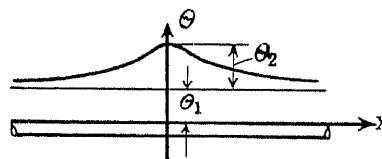


FIG. 1

- a. by current in the copper conductor
- b. by current in the sheath

leads us immediately to the following conclusions:

1. If the same temperature-rise curve is observed *irrespective* of whether the cable is heated in the copper or the sheath, then the variation in temperature rise must be ascribed to conditions *on the surface*, and the insulation is homogeneous.
2. If the temperature-rise curve differs materially depending on the mode of heating, its variation must, partially or altogether, be ascribed to heterogeneous insulation.

An expression for the equalizing effect of the sheath, on the assumption of constant copper temperature and negligible drop through insulation as compared to drop from surface to ambient air, can easily be derived. We get

$$\theta = \theta_0 + \frac{Q}{t A} \left[1 + \frac{E}{\left(1 + \frac{W^2 h \lambda}{T} \right) \text{Sin. } W x} \right]$$

where the thermal conductivity of the insulation has been assumed to fluctuate around a mean value with a small amplitude

E and a period x where $x = \frac{2 \pi}{W}$

The masking effect of the sheath thus manifests itself by cutting

the amplitude E down to $\frac{E}{\left(1 + \frac{W^2 h \lambda}{T} \right)}$

Otherwise θ = temperature at any value x

- θ_0 = ambient temperature
 T = heat dissipation constant
 A = total surface of cable sheath
 Q = total heat developed in copper
 h = thickness of cable sheath
 λ = lead heat conductivity.

For an ordinary cable, the factor $\frac{W^2 h \lambda}{T}$ would come out

about 0.1 so that the equalizing effect of the sheath is not very serious for fluctuations of a reasonably long period. For such fluctuations, therefore, the temperature-rise curve gives a close picture of the variation in thermal conductivity along the cable.

H. L. Curtis: In these two papers we have had presented to us some statements regarding air condensers. In one of them the authors have drawn the conclusion that when the humidity is above 40 or 50 per cent there is a loss in the air condenser. The authors of the other paper, I believe, do not get any loss until the humidity is about 80 per cent. In neither case do I think the data are sufficient so that we can judge whether there is a loss in the air itself or whether it is a question of a loss in the solid insulators which support the plates of these air condensers.

T. S. Taylor: I should like to ask a question in regard to the construction of the condenser; in particular, is the insulation supporting the plates at all in the field set up by the condenser? Again, is any attempt made to differentiate the factors relative to the losses in the insulation constituting the supports and the conduction losses over the insulating materials?

My experience in measuring power factor at extremely low values such as those of quartz, particularly at high frequencies, has led me to believe that the ordinary type of condenser does not enable us to detect the differences between the components that go to make up the total loss in the condenser. At the present time we have not been able to come to any conclusions as to the distribution of the losses among the various components.

Alexander Nyman: I had an opportunity a few years ago to make tests very similar to those described in Dr. Whitehead's paper in connection with impregnated paper condensers, and I am glad to be able to corroborate these tests. Our results were very similar.

In the first place we have to distinguish four factors in connection with impregnated paper condensers. There are the breakdown voltage, the life, the leakage, and the dielectric losses. The leakage is the thing that is most affected by humidity and moreover, by temperature, and the temperature is one factor, I believe, that is not brought out in this paper. We made a number of condensers and put them on long-time tests and observed the relation of leakage current, temperature, and humidity at the same time. We found that the effect of the temperature during the summer months, when the temperature goes up to 80 or 90 deg., was quite marked—more so than humidity. Now those were condensers which were completely impregnated in wax, and yet it seems that the moisture was able to penetrate through the layers of wax and affect the leakage.

Now as regards drying it is exactly as the paper states, you don't have to extract the moisture previous to impregnation. Impregnation, especially if carried out under a vacuum, will extract the moisture. Of course it is a different proposition in manufacturing. In manufacturing it may pay to extract the moisture before impregnation because there may be quite a large amount of moisture trapped and it would prolong the impregnation process too much. But as an actual improvement in the final quality, previous drying is not an important factor.

I should like to say something about what is in my opinion the most important quality in condensers, and presumably cables as well—that is, the life. Of course tests on leakage current and on dielectric losses probably have some bearing on the life, but the relation between these values and the life of the insulating material is not at all evident, and I believe that a much more satis-

factory way to predict the life of this material would be to determine by tests—probably very extensive tests—some kind of a law which would connect the life of a condenser with the potential applied to it. Both cable manufacturers and condenser manufacturers have conducted tests of accelerated life at higher than normal voltage, and two or three different laws have been suggested. Cable companies, particularly the British companies, have worked out one kind of logarithmic law to determine the life of a cable at excess voltage. Other laws are slightly different, just the usual power laws. In other words, the life of a condenser will be inversely proportional to a certain power of the voltage. Now these laws will give different results and it is hard to say which is the correct law. This is really a question of great practical importance to both manufacturer and user of every impregnated material. Such material is similar to incandescent lamps or many other electric products which have a definite life; what the life is going to be depends on how severe a service you subject it to.

If you produce a condenser, say, and want to know what is the rating you are going to apply to it, you have to know what the life of the condenser will be before you can decide at what voltage you are going to rate it; in order to determine the life it is either a case of conducting tests for ten years or so, or else applying some law that has to be found by actual tests to be correct. I should like to bring this point to the attention of the investigators.

A. W. Gray: I have been much impressed with the fact that apparently no satisfactory explanation has yet been offered to account for the so-called anomalous properties of dielectrics. The various phenomena described by Dr. Whitehead recalled to mind work that had been done in Berlin 25 years ago. I believe that this work gives a clue to a very simple explanation not only of these so-called anomalies, but even of specific inductive capacity.

The work that I refer to was not done upon materials used for electrical insulation, or with any idea at all of elucidating dielectric phenomena; it was done for the purpose of investigating the formation of ozone by the silent electrical discharge in the Siemens ozone generator. This apparatus is essentially a condenser with a composite dielectric consisting of two glass walls separated by a layer of oxygen or of air.

If such a condenser is charged it behaves much as any other condenser behaves until the intensity of the electric field becomes sufficient to break down the insulation of the gas layer and cause a sudden passage of electrons across this layer from one glass plate to the other. This passage is accompanied by a flash of light and by a sudden increase in the charge of the condenser. In addition, there is some comparatively slow passage of electricity from one side of the gas layer to the other by surface leakage along the bounding glass walls. When the composite condenser is discharged by connecting its electrodes together, there is another sudden passage of electrons across the gas layer, in the reverse direction; but this passage ceases when the potential gradient falls to a certain minimum. After this, the discharge continues slowly because of internal leakage around the gas layer. If the electrodes of the condenser are disconnected while the leakage progresses, residual charges on them become evident when they are again connected together.

Every substance, no matter how pure it may be, or how good an insulator it may be, must contain minute spaces distributed among portions that insulate more or less perfectly. These spaces may be bubbles or intermolecular spaces or interatomic spaces or even intra-atomic spaces. The insulating portions may be pictured as forming baffles that intercept electrons shot through the material by the action of an electric field. The conduction current that persists after the field has been established may be pictured as consisting of electrons that succeed in penetrating the baffles and of electrons that are passed on by some procedure analogous to elastic impact. When the substance

forms the dielectric of a condenser, the normal currents of charge and discharge may be thought of as arising mainly, if not wholly, from sudden passages of electrons across spaces bounded by layers of baffles. Leakage around these spaces could account for the phenomena associated with dielectric absorption. Such leakage could result from even traces of conducting substances dispersed throughout the dielectric. Since the capacity of such a composite condenser must depend upon the internal structure of its dielectric, it follows that, in general, different substances should be expected to exhibit different specific inductive capacities.

This view conforms to all the essential requirements of Maxwell's theory of heterogeneous dielectrics. For Wagner's artificial assumption of conducting spheres imbedded within a pure dielectric medium without conductivity, it substitutes an internal structure known to exist in every substance. I have not yet learned of any dielectric phenomenon—normal or anomalous—that does not seem to be a natural consequence of actions similar to those observable on a larger scale in a Siemens ozone generator.

An ozone generator can be made to yield information for quantitatively testing deductions from the hypothesis that I have just outlined. For example, electricity passed through the gas layer does work in converting oxygen into ozone and ozone into oxygen. By suitable construction of the generator, internal surface leakage can be rendered negligible, so that the quantity of electricity passed through the gas can be determined from electrical measurements that are fairly easy to carry out. When oxygen flowed through such a generator fast enough to eliminate the de-ozonizing action of the silent electrical discharge, I found, among other things bearing upon dielectric behavior, that the mass of ozone produced was directly proportional to both the quantity of electricity that passed as conduction current through the gas and the difference of potential applied to the electrodes, that is to say, directly proportional to the electrical work done upon the gas. Energy similarly expended upon air occluded within the insulation of a power cable means power-factor loss as well as production of ozone, which should be more active than ordinary oxygen in causing deterioration of the dielectric.

Those interested can look up my original papers.¹ They will find there accounts of such things as the effect of water vapor in the gas and the effect of reducing the suddenness of charge and discharge by inserting a high resistance in the electric path, as well as a description of a method that I devised for using a ballistic galvanometer to measure a single charge, or discharge, while the modified Siemens ozone generator was alternately charged and discharged rapidly at various potentials ranging up to over 12,000 volts.

J. B. Whitehead: There has been a number of suggestions from time to time that dielectric absorption arises in the absence of homogeneity of the dielectric itself, and I understand that the suggestion of Dr. Gray is that air spaces through the combination that they offer of leakage paths and also the presence of gaseous ionization, will lead to the ordinary phenomena of dielectric absorption as we know it.

T. F. Peterson: One phase of the second paper is particularly interesting to me and I should like to go into it in some detail. To me the results expressed in Figs. 13 and 14 are very striking and indeed, at first thought, seemingly peculiar. They are obtained on what we might consider, in the light of the work done here, poorly impregnated paper, which contains a considerably greater percentage of air than the ordinary samples tested. The explanation offered for the improvement in the power-factor—voltage curve of Fig. 14 seems to be along the right line but probably could be somewhat amplified. The authors have recognized that this rejuvenation of the cable, as we might call

it, due to voltage applications, exists, and have accounted for it by saying that the air has either disappeared or has gone into combination with the oil, or something equivalent has taken place. In any event, they claim that it is not due to the entrance of compound from the outside. I do not think that the tests made would warrant forming such a conclusion.

At the Winter Convention of the A. I. E. E. we had a paper by some Russian experimenters on *The Influence of Internal Vacua and Ionization on the Life of Paper Insulated High-Tension Cables*,² and in a discussion of it I derived a theoretical power-factor—voltage curve which was very similar to the ones obtained by these experimenters and others. Curve *A B C D* shown herewith in Fig. 2 is typical. At low voltages we have a range of constant power factor. Then, with increase of voltage, a certain stress is reached at which there is an increase in power factor, the curve finally reaching a point where it bends down and becomes negatively sloping. The point at which the increase in power factor takes place is dependent on the thickness of the films at the conductor and also the pressure of the gas. As the voltage increases there is a spreading of the volume of gas in ionization until some point is reached where all spaces are ionized, and then there is a dropping off of the power factor. The curves obtained by plotting the equations which I have derived have been checked up fairly well by experiment.

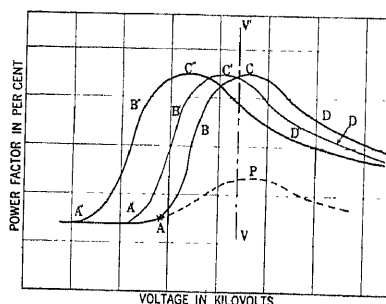


FIG. 2

The point I wish to emphasize is this. Point *A* depends on the pressure of the gas since the value of the stress at which the ionization takes place is proportional to the pressure. Now as the air is absorbed by the compound or is combined in some way with the paper, the pressure will undoubtedly be reduced, and I think to explain fully the characteristics obtained in this paper, we have to consider this. As the pressure changes curve *A B C D* will be moved over to *A' B' C' D'* and we could have a series of curves depending on internal pressures, the lower the pressure the farther left will the curve be.

Now the power factors obtained and plotted in Fig. 13 are for constant voltages. If, with a line plotted through *V V'*, a constant voltage, we consider the power-factor curves moving over with speed proportional to the decrease in pressure and then plot power factor at voltage *V V'* against time we would have a curve such as that given in Fig. 13. This appears to be a partial explanation for the improvement in power factor observed.

In Fig. 14 we have two power-factor curves; one is obtained before any voltage has been applied and is of the characteristic type. It is quite conceivable, due to the slow movement of the compound in cable, that after this application of voltage, the pressure is considerably less than atmospheric. This, in itself, may result in power factor decrease. It may also promote movement of compound into cable which will also assist in this direction. The point at which curve *A B C D* begins to rise is dependent, as I said before, on the pressure in voids and also on the thickness of them. The slope of this curve is dependent on the percentage of these spaces throughout the cable. When the pressure of the gas within the cable is reduced during this

1. "Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften;" 46. 1016. 1903; *Ann. der Physik*: 13. 447. and 15. 606. 1904; *Phys. Rev.*: 19. 347. 1904.

2. See page 731.

test, as the air is combined with the oil, presumably the volume or the percentage volume will remain the same if no compound enters the cable. If compound does enter the cable the characteristics will change and instead of getting curve *A B C D* one would probably get a flatter curve, such as *A P*. In any event, either the reduction in pressure during the test or the entrance of compounds would tend to give us this flat characteristic which is the second one obtained in Fig. 14. Which is the predominating influence is difficult to say because we do not know whether the rate of the reduction of pressure due to the combination of air with the compound is greater than the rate of entrance of the compound. We should have to have some idea of the relative values of those two changes with time before we could say one way or another which was the important influence. I do think, however, that either one can explain the characteristics in some measure.

S. J. Rosch: I believe, after reading this paper, that in presenting the data it has been the intention of the authors to attempt to shed light on some of the obscure fundamentals of dielectric phenomena as occurring in a lead-covered impregnated-paper cable. The cable model as constructed by the authors was an ideal one since the physical relationships between the conductor, insulation, and outer sheath remained constant throughout the experiment, whereas in actual practise the insulated cable receives a number of bending cycles during the various operations before lead covering, and after lead covering during the installation in the ducts, thereby introducing various voids in the insulation proper and between the outer layers of insulation and lead sheath.

Furthermore, for the reasons just mentioned, the electrical characteristics of the cable on the reel in the factory may be entirely different from those obtainable on the cable after pulling through the ducts. Then again, during the entire time when these tests were conducted on the model cable, the latter was completely submerged under oil, a condition entirely foreign to cables as ordinarily manufactured and tested, and only comparable to the conditions accompanying the testing and operation of the oil-filled 132-kv. cables.

However, the data presented in this paper should be of paramount importance to the cable manufacturer, as they indicate an acme of perfection in characteristics not obtainable at present on a commercial scale it is true, but as a desirable goal for the manufacturer to strive to attain in the cables of the future.

I believe, however, that the value of the paper would have been enhanced considerably, if some of the measurements, such as those used to obtain power-factor—voltage curves, could have been continued at temperatures below 29 deg. cent., such as 0 deg. cent., —10 deg. cent., and —18 deg. cent., as representing conditions actually met with underground in Chicago and other parts of the country. It would really be of interest to note how the ideal cable would have behaved under these temperatures and whether the compound used would have contracted under the cooling, thereby perhaps causing void formation and producing a different form of ionization curve.

If this research is to be continued, I would suggest that the experiment be repeated but this time using a flexible stranded conductor, the tests being made before and after bending the cable, so as to study effects approaching as nearly as possible those encountered in actual cable practise. I suggest this merely with the thought that a consideration of these parallel data, obtained by the same experimenters, might throw some real additional light on a phase of electrical engineering still woefully obscure.

G. M. J. Mackay: Dr. Whitehead's paper emphasizes the fact that in drying cable, applied vacuum simply increases the rate of moisture removal because of the more rapid diffusion of water vapor into the lower ambient pressures. There is no mysterious "pulling out" effect produced by a vacuum pump.

However, it is not quite clear from the paper how the various

pressures were maintained. For instance, when a pressure of 5 cm. is specified in Table I, does this mean that the pump was kept running and a constant rate of leak into the apparatus maintained, or that the pump was shut off after a pressure of 5 cm. had been reached? In the latter case, of course, water vapor would not be so thoroughly removed, if at all, and the dryness of the paper would be entirely independent of the pressure of gases other than water vapor itself. Perhaps the relative rate of leak may explain the unexpected improvement found at pressures of 3 mm. Most vacuum pumps do not completely eliminate water vapor from a system because of compression of the vapor to liquid which re-evaporates into the system. Drying agents therefore should be used as near as possible to the material to be dried. The lower the pressure, the more rapid will be the absorption of water vapor by the drier, so that this also may be a factor in the increased rate found at 3 mm.

We have investigated the effect of vacuum on both electrical characteristics and endurance by treating in the laboratory 20-ft. lengths of cable with 9/32-in. insulation, subjecting them to vacuum treatments with pressures varying from 25 mm. to 0.1 mm. and in some instances using liquid air to condense the water vapor. No appreciable difference was found either in characteristics or in life, although these experiments being made with ordinary cable, the effect of such variables may have been masked by the greater effect of voids.

Cable equal in quality to that prepared by the usual methods has also been made by submersion of undried lengths in oil although we have used for this purpose somewhat higher temperatures than those applied by Dr. Whitehead.

We feel that it is decidedly unsafe, however, to carry the conclusion (No. 8) of "the relative unimportance of air pressure of impregnation within a fairly wide range, say up to 15 cm." to the manufacture of long lengths of cable with insulation $\frac{3}{4}$ in. thick. With the relatively short specimens and thin insulation used by Dr. Whitehead in his experiments comparatively little gas may be trapped. But with a length of cable having insulation $\frac{3}{4}$ in. thick, impregnation at even 1-cm. pressure may result in undesirable gas pockets. Under the worst condition with compound admitted suddenly and advancing from both ends and the circumference simultaneously, the residual gas at 1/76 atmosphere may be compressed into a single large bubble, which if none escaped, would mean a pocket at atmospheric pressure of 1 ft. in length for every 76 ft. of cable. Either special methods to eliminate this residual gas, or the use of the best vacuum obtainable seems necessary if internal ionization is to be eliminated.

As a matter of fact, oil-filled cable for 132,000 volts is exhausted at pressures always less than 5 mm. and usually below 2 mm.

W. A. Del M r: This work of Dr. Whitehead and his associates is, in my opinion, very valuable and useful to all of us interested in this problem of cable manufacture, because it tells us the properties of a type of cable which must be avoided at all hazards, namely, the perfectly oil-filled cable.

It was my hope and expectation both that the authors would make a perfect cable, not an air-free one, in order that we might have a standard by which we could measure our less perfect commercial products, and that they would ascertain the effect of variations in process upon the quality of the dielectric produced.

The air-free cables made by the authors will probably have zero value from an operating standpoint, if lead-sheathed. If tested under operating conditions of temperature and pressure cycles, I surmise that they will make a very poor record, because the sheath will stretch permanently at high temperatures and high vacua will form at low temperatures, permitting destructive ionization to bring the cables to an untimely end.

The thoughtless will deduce from these tests that the lower the ionization and the higher the dielectric strength, the better the cable. This does not follow. In my opinion present-day cables

have gone beyond the optimum operating values of these quantities.

The work of Dr. Whitehead and his associates, moreover, seems to come to an end at the point where the really big problems of the manufacturer begin. The big problems of manufacture in impregnation relate principally to dealing with large masses of material and with time limitations. That is to say, one has to consider the movement of air and the movement of oil in large masses, and in the case of the experimental work in this paper those two elements of mass and time are not taken into account. The authors may say, of course, "We stop where you manufacturers should take up the problem," and perhaps that is right, but there are several places in the paper where one would not get that impression. For instance, on the first page occurs the sentence: "The following studies were undertaken in the hopes of throwing some light on these questions," that is to say, the reconciling of two very widely different methods of manufacturing cable. I do not see that experiments on 4-ft. lengths of cable, with the quantities of oil used, throw any light on the relative merits of manufacturing processes.

In order to understand the drying, evacuating, and impregnating processes, the rates of flow of moisture, air, and oil, the masses of water, air, oil, and paper, the nature of the available equipment, and the time commercially available, are the main factors which must be studied. Of course, the authors have not considered these factors, but they have written their paper as if the factors in question are negligible. For instance, it is stated that it is "only at impregnating pressures about 25 cm. Hg. that the typical rising break in the power-factor—voltage curve begins to be evident." This value of 25 cm. is given as a constant, whereas in reality it is only an accidental value depending on the capacity of the particular vacuum pump used in the experiments. In the impregnation process used in these experiments there is a race between the rising oil and escaping air. The authors say that their experiments indicate the air wins the race if the vacuum is better than 25 cm., but they should say that the air wins if the oil does not rise faster than 96 ft. per day, (or whatever the rate may have been) the connection between this rate and the 25-cm. vacuum being dependent on the capacity of the vacuum pump which is sucking up the oil.

I am puzzled by conclusion No. 1, which states: "For the drying of cable paper before impregnation, preliminary drying before vacuum treatment is unnecessary, except perhaps as a convenient method of driving off a large part of the water always found in cable paper." Of course, that is the thing we are all trying to do.

No conclusions should be drawn from the experiment on the change of power factor with continued application of voltage until it is studied under more practical conditions, as it is probably a phenomenon peculiar to the test conditions and not to cable in general. If the cable is tested in long lengths, pressure equalization will take so much time that local dielectric heating may cause pressure instead of increased air spaces, thereby giving an entirely different ionization-time curve than obtained on tests of an open 4-ft. length.

I should like to make sure, in places such as Fig. 10, where it says, "impregnated at 30 cm." that that means absolute pressure.

In conclusion I would couple my praise of the excellence of the laboratory work with a caution against drawing conclusions therefrom without giving full consideration to large-scale manufacturing conditions and the modifying effect of temperature and pressure cycles in service.

W. S. Clark: The information I am giving comes from the Commonwealth Edison Company. About six months ago they installed some lengths of 132-kv. cable under pressure. They also installed a Schering bridge so that they could make power-factor measurements. There were three or four samples of cable there and I don't know which sample is which except the sample which is oil-filled and which is quite easily distinguished because it is the only one that has shown no change in its electrical

characteristics since installation. It comes nearer to what we want as a cable and for cable insulation than anything we have yet had. On the broad question of oil-filled cable—you might say that all cable is oil-filled—but what I mean is cable with reservoirs of oil under pressure,—the use of the ordinary type of cable where the static pressure varies with the temperature of the cable, will have to be worked out on an economical basis. For some voltages it will be advantageous to use an oil-filled cable. For some lower voltages it will be economically better to use the other. But the oil-filled cable so far has done what it was expected to do. In the operating circuits, entirely apart from the circuit I have spoken of, there have been no electrical failures since last June in Chicago and last August in New York, and that includes joints.

F. M. Clark: Any discussion concerning the drying of cellulose materials for electrical purposes must define what is meant by the term "dry." In Pittsfield we have found that a sheet of paper may be placed in a 100-deg. cent. oven and dried to a constant weight in approximately 24 hr. If impregnated in this condition the power-factor characteristic will be similar to that described by the authors, yet we do not consider such material dry. Up to this point apparently all that has been done is to remove a large part of the absorbed moisture. To remove more water and to obtain what we term a dry sheet suitable for high-voltage electrical apparatus such as capacitors we have found that a somewhat prolonged vacuum treatment is essential. The actual weight of water removed from the insulation during this stage is not great. The effect on the dielectric characteristics of the insulation, however, is marked, the insulation resistance rising to a high value and power factor dropping well below 0.25 per cent. We believe that in this last stage of the drying process we remove completely all traces of absorbed water together with some water of hydration from the cellulose molecule.

Figs. 3 and 4 illustrate what is termed by the authors as satisfactory behaviour. The effect of voltage on the power factor is absent at low temperature but becomes somewhat more pronounced at higher temperatures. An inspection of Fig. 3 shows that for a constant voltage stress the power-factor—temperature relation varies with the stress applied. At 60 volts per mil, for example, it shows a minimum power factor at approximately 40 deg. cent., whereas at 300 volts per mil the power factor rises rather sharply from room temperature. With Fig. 4, however, the characteristic "V"-shaped curve is obtained at all voltage stresses. It is a characteristic of what we term a well treated dielectric to possess a "V"-shaped power-factor—temperature curve with its minimum value at approximately 35 deg. cent. and a power factor at 50-60 deg. cent. which is approximately equal to that shown by the insulation at 25 deg. cent. The authors' curve of Figs. 3 and 4 shows comparatively high power factor at 55-60 deg. cent.

We have in many cases noted a temporary rise in power factor during the early stages of an over-voltage run and have credited it to about the same causes as have the authors—the dissipation of entrapped air or residual traces of water vapor. However, we have not been convinced that ionization is necessary to remove such residual gases. It has been our experience that, even without voltage, gas bubbles trapped in an oil dielectric will disappear in a manner which indicates that the gas is being removed by the process of solution.

The authors in conclusion No. 1 see no reason for a preliminary air brake except as a convenient method for driving off a large part of the water present. As far as I know no one has advocated a preliminary air brake for any other reason. Their conclusion No. 2 states that it is impossible to dry insulation with a pressure of higher than 5 mm. of mercury; yet it is possible to dry in air at atmospheric pressure. It is hard to reconcile such statements unless with the experiments made under 5 mm. of pressure the drying box was tightly sealed in order to hold the pressure constant at this value. Such a static condition cannot

be compared with the ordinary conditions present in vacuum treatment where leakage introduces a steady current of air through the treating tank. It is, of course, impossible to dry insulation completely in a "dead" space where a water-vapor equilibrium is soon established between the insulation and the surrounding space.

G. B. Shanklin: In regard to the ionization characteristics in the paper by Dr. Whitehead and his associates, from the experience we have had I would attribute the greater part of the unexpected results to the fact that their cable samples were in a bath of compound. We have found that that is the ideal condition; if we could build cable and keep it in a bath of compound we could ask for nothing more. I do not mean, in making this statement, to give the impression that their work is not of extreme value. A fresh point of view and a different way of making the tests is always helpful, but the conditions we have in the actual manufacture of cable, in large vacuum chambers, on large reels, leading those cables and preventing void formation, are really very different from the type of research work which they have conducted. As Mr. Clark pointed out, the liquid oil-filled cable will approach the condition of their research work more closely than a cable filled with heavy compound.

D. W. Roper: In Fig. 13 of the paper it will be noted that there is an increase in the power factor with time during the first few minutes following the application of the test voltage. This is the only curve which shows this peculiarity and this curve was taken from a cable sample that was purposely made of poor quality. Professor E. B. Paine, in some investigations that he is making at the University of Illinois, obtained a similar curve from a sample of cable known to be of poor quality that was sent to him for testing purposes. We have recently in Chicago made a life test on a sample of cable showing a similar curve, that is, an increase in the power factor in the first few minutes after the application of the voltage. This test resulted in an unexpectedly short life for the sample of cable as indicated by the other quality tests which had been made in advance of the life test. It is suggested that this point be given careful attention as there is some possibility of this increase in power factor during the first few minutes after the application of the voltage being a more accurate indication of the life of the cable than the actual value of the power factor itself.

R. W. Atkinson: I think we have had the first presentation of absolute measurements of the dielectric-loss characteristics of the air condenser, which itself has previously been taken as an absolute standard of capacity and power factor. Now, we have measurements on the air condenser checked against standards even more fundamental. Certain limitations have been shown, in respect to humidity, for the air condenser but it is shown further that, under the usual conditions of use, the air condenser is correctly used as it has been used and is, within the limits stated, an exceedingly satisfactory unit for the purpose.

In the earlier discussions of the paper on residual air and moisture it has been truly said that the measurements are under conditions which are different from those in the factory. It is, however, perhaps this very fact that gives the paper its greatest value. There are already numerous data about the characteristics of cable made under factory conditions. Here we have a set of data about cable made under very carefully controlled conditions, and with these conditions varied in a controlled manner. The application of these conditions, as has been pointed out, is not a matter for an amateur, but it is proper to emphasize that the very real value of this study is due to its uniqueness.

R. J. Wiseman: I am going to say only a few words with respect to the cable manufacturer's point of view on the paper of Dr. Whitehead and his associates. I am in agreement with what others have said in regard to the limitations of cable manufacture. There are some points I should like to have considered, not only from the electrical point of view but also from the physical.

Under Conclusion 4, they say "for thoroughly dried paper," etc. We must define "thoroughly dried paper." We can dry paper to the point where it is destroyed and get very good electrical values. However, cables are made to operate for many years. Shall we stop at 0.1 per cent moisture or shall we stop at 0.02 per cent moisture or even go to 0.01 per cent? That is something the cable manufacturer must consider at all times. 0.03 per cent moisture is very readily noticed on the paper by its brittleness. A 0.1 per cent gives good electrical characteristics and longer life. However, the power factor is slightly higher than what we get for 0.03 per cent moisture. Which do we want? From a cable manufacturer's point of view I would say 0.1 per cent if you want to get life out of your cable.

Referring to Figs. 5 and 13, the variation of power factor with time which Mr. Roper has referred to as showing that power factor will vary with time, really is not very great. It is a pretty flat curve from a commercial point of view, only changing 0.05 per cent. It is a good idea to make the ionization test at the beginning and end of a voltage test such as the 24-hr. test we are now making. If the power factor does not show a large increase it can be considered good cable.

With regard to Conclusion 8, I can hardly agree with the statement that:

"We conclude, therefore, that the sharply rising curves and rapid changes in power factor, often noticed in commercial cables, are due to relatively large and extended areas of entrapped air or gases resulting either from imperfect impregnation, distortion in handling, or temperature expansion of the lead sheath."

This may be entirely correct for the rapid changes in power factor but not for the sharply rising curve of power factor, particularly for the higher temperatures. This can be a function of the nature of the compound used. Some use rosin in the compound which gives a slightly increased power factor at higher temperatures, and even at the lower temperatures without rosin you can get a slightly changing power-factor curve. The curve is really a function of the kind of materials used.

C. L. Kasson: (by letter) In regard to the paper entitled *A Thermal Method of Standardizing Dielectric Power Loss Equipment*, I should like to point out that no comparison between the values obtained by the thermal and electric methods is correct unless the latter method makes use of electrical shields as well as guards.

Dielectric loss, as usually measured without shielding, includes the loss in the material and the loss in the adjacent air. Under some conditions the watt loss in the adjacent air may be greater than that in the material itself, thus introducing a large error into the unshielded measurements. This was shown in a paper by the writer entitled, *High-Voltage Measurements on Cables and Insulators*,³ given at Pittsfield, Massachusetts, May 27, 1927, before the A. I. E. E. Regional Meeting.

In order to secure accurate comparisons between the thermal and electrical methods of measuring dielectric loss it will, therefore, be necessary that the electrical measurements be made using a system of complete shielding of the material, its connections, and measuring equipment.

R. W. Chadbourn: (communicated after adjournment) Messrs. Scott, Bousman, and Benedict have developed an ingenious and electrically simple method of checking watt-loss measurements on cables. It is unfortunate that the scheme involves such an elaborate set-up and so long a time period to produce steady conditions that its application would be very limited in the laboratory of an operating company—the very place where it might perhaps be of most value.

Considerable care must be taken that the sheath radiation is not affected by external air currents (this requires the use of an enclosed test box of large dimensions), the sheath temperatures must be carefully and accurately determined, and the test must be prolonged over a period of many hours, until the heat flow

3. A. I. E. E. TRANS., Vol. XLVI, 1927, p. 646.

through the cable reaches a steady state. Because of these considerations, it seems to me that the scheme is chiefly of value to determine, once and for all, for a number of laboratories, the probable accuracy of any direct method of measurement, as with dynamometer wattmeter or the like, or to compare different dielectrics for cable use, where, perhaps, the most accurate possible knowledge of dielectric properties may be important.

It should be borne in mind that the measurement of dielectric loss in cables is not, in general, a precision test and that, except in rare cases, a high order of accuracy is not required nor expected. On installed cables, for instance, temperature variations along the cable introduce a variable of such magnitude that accuracy of more than 5 or 10 per cent is, in most cases, impossible. The important thing—in fact, all that can be hoped for—is to be able, by dielectric-loss measurements, to detect cables whose loss is so high that their condition may be definitely questioned, or which show, by a progressive change at given temperature conditions, evidence of gradual deterioration. There are now available, for installed cables, direct methods of measurement, the accuracy of which is known to be entirely satisfactory.

For laboratory measurements involving, in many cases, very short lengths of cables, the temperature variable can be readily eliminated, but this advantage is partly offset by greater difficulties of measurement, due to the smaller quantities measured and the errors introduced by end leakage. The latter can be practically eliminated by proper shielding and guarding, and at the present time portable wattmeters are available for use at very low power factors, of such range that measurements can be made at moderate voltages on lengths of cable as short as 25 or 50 ft., or with some types of cable, 10 ft., with sufficient accuracy for commercial comparisons.

C. F. Hanson: (communicated after adjournment) The authors of the paper on *Residual Air and Moisture in Impregnated Paper Insulation*, express a little surprise that Sample Group No. 36, which had no preliminary drying but was immersed in the impregnating oil while the applied paper insulation was at room condition in regard to moisture content, should possess good electrical characteristics. According to my experience, both from the point of view of laboratory performance and that of cable manufacture, I should be disposed to place my wager on Group No. 36 in preference to any of the other groups. I have found that the less the untreated paper is exposed to heat, the better will be the finished product, particularly in regard to dielectric strength. A decrease in the dielectric strength of the oil-impregnated paper due to exposure to heat prior to impregnation will be manifest long before any deterioration can be detected in the physical properties of the paper. If the burden is not too great, I suggest that the authors try to process a group by using a temperature of about 90 deg. cent. or even less in the preliminary and in the vacuum drying. Toward the end of the vacuum-drying period the temperature could be raised to 105 deg. cent. in order to facilitate impregnation when the oil is introduced and also to obtain an impregnating process comparable with that of the other groups.

The authors seem to prefer the power-factor—voltage gradient characteristics shown in Fig. 4 to those shown in Fig. 3. I have noted no data in this paper nor in the authors' previous paper to confirm this preference. I doubt whether anyone at the present time can produce laboratory data which would be conclusive. A laboratory test which will produce unqualified evidence as to the suitability of a cable for service performance is still lacking. Perhaps the best test available now is a long-time voltage test, usually referred to as a life test. I shall await with interest the results of the authors' life test on these various groups.

Below are given data of the power-factor—voltage gradient of two specimens of treated paper. Each specimen consisted of two disks of paper 30 cm. in diameter. These were dried in a current of air at 100 deg. cent. for 72 hr. This temperature was used because no means for vacuum drying were available. The

paper was then immersed in the impregnating compound for 18 hr. at 100 deg. cent. under atmospheric pressure. The specimen was then assembled between brass disk electrodes immersed in a pan of the impregnating compound. An attempt was made to remove all visible bubbles of air. There may have been present small invisible air voids due to the method of impregnation. Both specimens were intended to be alike with the exception of the impregnating compound. Specimen A was impregnated with a high-specific-gravity and high-viscosity oil containing 15 per cent of rosin. Specimen B was treated with a mixture of petrolatum and a low-specific-gravity and low-viscosity oil and containing no rosin. It will be noted that specimen A has a power-factor characteristic at 79 deg. cent. similar to Group 36 in Fig. 3. Specimen B has a characteristic similar to that given in Fig. 4. The characteristics of both specimens at 23.5 deg. cent. were flat corresponding to Fig. 3 and Fig. 4.

Volts per mil 60 cycles	Power factor at 79 deg. cent.	
	Specimen A	Specimen B
55	0.014	0.051
75	0.015	0.049
100	0.016	0.044
150	0.019	0.037
200	0.021	0.030
250	0.023	0.026
300	0.026	0.022
350	0.029	0.020

These specimens were subjected to a life test with the following results:

Stress applied 60 cycles Volts per mil.	Temperature 80 deg. cent. Hours application of each stress	
	Specimen A	Specimen B
500	46	46
600	141	1.7 Failed
720	10.5 Failed	

The foregoing data are not conclusive by any means but they do suggest that the characteristic of Group No. 36 in Fig. 3 may possibly be preferred to that of Group No. 4 given in Fig. 4.

W. N. Eddy: (communicated after adjournment) It is suggested that the authors' first conclusion—that *atmospheric drying* before vacuum treatment is not necessary for the drying of cable paper—is not justified by the data given. Instead, the test results seem to indicate that *vacuum treatment* is not necessary for the drying of cable paper. On the second page of the paper the impression is given that a 3-cm. deflection was obtained after 48 hr. at 105 deg. cent. atmospheric pressure, which is practically as low as any of the deflections obtained in Table I with the aid of vacuum. Also, it should be remembered that pressures below 1 cm. are impractical for factory drying equipment. Table I and Fig. 1 indicate that 24 hr. at atmospheric pressure followed by 24 hr. at 1 cm. pressure (8-12 cm. deflection) did no more complete drying than 30 hr. at atmospheric pressure (8 cm. deflection).

The authors' tests indicate that the pressure and time of drying do not have a controlling influence on the quality of the insulation as shown by the power-factor—voltage curve—in other words, that the presence of some air and moisture in the insulation does not cause increased ionization. The writer is interested in a paper recently completed in which evidence is given that the presence of some air and moisture may actually decrease the ionization, confirming the authors' flat power-factor—voltage curves on insulation saturated without previous heating or vacuum treatment.

The general lack of ionization shown by the authors' samples in spite of a wide range in drying conditions is further evidence that the principal cause of excessive ionization and premature failure in high-voltage cable insulation is the formation of contraction voids during cooling, both in the factory tanks and in service. The type of sample and conditions of impregnation

and testing used by the authors would indicate that their insulation, as compared with actual high-voltage cable insulation, should be relatively free from such voids and, therefore, of superior quality. To mention another example of the great increase in quality caused by minimizing the formation of contraction voids, cable paper of low air resistance can be impregnated in sheet samples 21 mils thick without previous drying merely by 20-min. immersion in hot compound, so that it will withstand 15,700 volts (750 volts per mil) for 5000 hr. at room temperature. It is thus evident that when working with miniature samples of insulation it is often surprisingly difficult without lowering the saturation temperature to impregnate the insulation so that its quality is anything but satisfactory. As the most desirable method of improving the quality of cable insulation is to study its weaknesses, these characteristics of miniature samples constitute a serious objection to their use.

The authors find no material increase of power factor with time on voltage. Similar results have been obtained with 10-ft. cable samples on overvoltage in the laboratory at room temperature, with the cable ends unsealed. Fig. 3 herewith shows

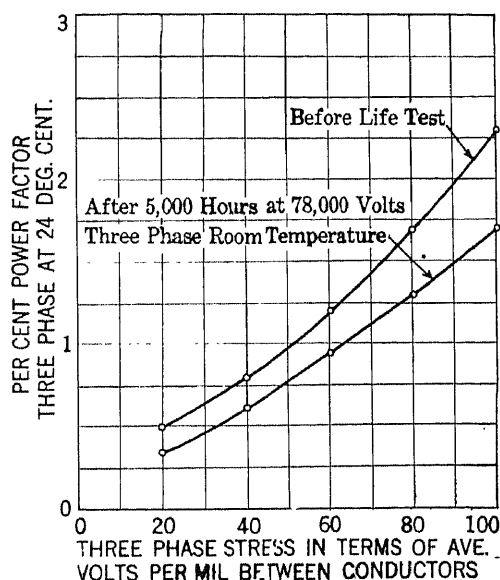


FIG. 3.—POWER FACTOR OF THREE CONDUCTOR BELTED CABLE 33,000 VOLTS WORKING PRESSURE

that 5000 hr. of 78 kv. 3-phase on a 3-conductor 33-kv. belted cable under these conditions resulted in a slight decrease in power factor with little change in curve slope. In view of the material increase of power factor often found on cable in service, the constancy of the power factor on the authors' samples and the cable samples suggests that neither test condition approximates actual service conditions closely enough to make the test entirely satisfactory as a criterion of cable insulation quality (its behavior in service). The principal disadvantage of the cable life test may be that the temperature is too uniform and the cable ends not sealed. In addition, the authors' tests have the disadvantage that the insulation is thin.

In general, it is believed that the authors' carefully made and interesting tests offer another example of the great difficulty in applying the conclusions of tests made under typical laboratory conditions to the manufacture and use of actual high-voltage cable insulation. It is becoming more apparent that what have been considered the most reliable indications of insulation quality available in the laboratory, the overvoltage life test and the power-factor-voltage curve, often fail to give a reliable indication of the relative behavior of the insulation in service, and that the principal difficulty is not the nature of the test but the conditions

under which it is made. While the relatively constant-temperature, constant-pressure conditions of the laboratory tests tend to decrease the number of contraction voids, the variable-temperature, constant-volume conditions in service tend to increase the number of contraction voids.

J. A. Scott and H. W. Bousman: Mr. Davidson's caution about guard-circuit potential is timely. We do not think anyone should either ground his guard circuit or try to raise it to the proper potentials without due care. Particularly this is true with bridge circuits.

Referring to Fig. 7, the capacitor plate spacing is 11 cm.

Mr. Bratt's discussion of heat flow in a cable was very interesting and we hope he will find opportunity to amplify it. For example, we can find no indication that the surface temperature rise of a cable with a "hot spot" is typically a constant plus a normal frequency function, as given by him. There are considerable experimental difficulties with his proposed method for measuring thermal conductivity differences, a measurement which should precede a foot-by-foot comparison of heating test.

How long before failure does a "hot spot" develop?

We may as well admit to Dr. Curtis that so far as we can determine no one has made any conclusive experiments showing appreciably more conduction current in the electric field in moist clean air than in dry air. Our capacitor plates are supported by treated wood carefully kept out of the field, and we were able to repeat the measurements shown in Figs. 7 and 8 over a five-month period. We think there is a conduction current of the order of magnitude shown through the space between the plates. Dr. Kouwenhoven's work with filtered air is in the right direction.

J. B. Whitehead: Our point of view in planning the experiments described in the paper has been to isolate, as far as possible, the influence of air and of moisture on the performance of impregnated paper. In order to carry out this isolation it has been necessary to eliminate numerous other factors and conditions which necessarily are present in prevailing methods of manufacturing paper-insulated cables. In other words, we have been studying the fundamental properties of impregnated paper as influenced by air and moisture, quite without reference to the question whether or not it is possible to preserve and protect these properties completely in paper insulation, as assembled in a manufactured cable. The purpose of the investigation has been, therefore, to call attention to the principal differences which obtain between carefully controlled impregnated paper and impregnated paper as it actually functions when applied to a cable. We offer no excuse for this point of view; quite the contrary. We merely call attention to the fact that this is the method adopted in every scientific investigation which aims to uncover the causes of existing troubles. Naturally we shall be more than pleased if manufacturing methods can be improved so that the manufactured cable will approach more nearly the apparently desirable characteristics of some of our specimens.

We believe that many of the comments that have been made on our paper have been made without complete recognition of these facts. We by no means suggest that the processes we have followed in preparing our samples should be followed in manufacture, nor that any of them should be taken as a standard upon which a cable specification might be drawn. We do, however, believe that the relative differences to which we have called attention, among drying processes, impregnating processes, and resulting performance, are in general correct, and can be made use of as bases for changes in manufacturing methods.

For example, some of the comments of Messrs. Del Mar and Mackay have been directed towards possible variations in our results as affected by our methods of evacuating the impregnating chamber and holding the pressure constant. We believe that variations of the character mentioned are quite possible. We do not, however, believe that these variations would be very great. Moreover, as we have followed approximately the same program for all of our samples, we think that the variations

so caused would not be great enough to influence the generality of our conclusions.

In direct reply to Dr. Mackay's question the pump was kept running during admission of compound. The rate of admission was adjusted so that the air pressure was maintained at the particular value under test. Departures from this occurred at the higher pressures owing to the limited capacity of the pump.

Answering Mr. Del Mar, the values of pressure are all given in terms of centimeters of mercury absolute pressure.

We have been much interested in Mr. Hanson's preference for the power-factor curves of Fig. 4, over those of Fig. 3, and his suggestion that any sustained heating of the paper, even at moderate temperatures, tends to lower its insulating value. We hope to be able to report in the future on the life tests on these and other types of sample suggested by his comments.

W. B. Kouwenhoven: Dr. Curtis has raised a very important question as in both the Schering-bridge and the dynamometer-wattmeter methods of measuring dielectric loss an air capacitor is used in connection with the measuring equipment. It is important for the accuracy of the results that this air capacitor be loss-free.

Scott, Bousman, and Benedict mention the effect of humidity on air capacitors in their paper. During the summer of 1927 troubles which I ascribe to humidity developed in our air capacitor at the Johns Hopkins University. Using continuous potential I made some tests on an air condenser fitted with guard rings and so constructed as to keep the dielectric out of the electrostatic field. The area of the main plate of this condenser is 2260 sq. cm. and the spacing between the plates 2.5 mm. Using this condenser and a continuous potential of 60 volts per mm., I obtained a conduction current of 3.74×10^{-7} amperes, at 90 per cent relative humidity. This gives a value of power factor of 0.0008 for the air capacitor under alternating stress and the same voltage gradient as in the continuous-potential tests. It is interesting to note that this value is of the same order of

magnitude as that Mr. Hamburger mentioned, as having found during life tests on cable specimens using another air condenser, and that E. S. Lee's results also agree quite closely with this value.

It is very important to know if air capacitors are free from loss or not, and we are studying that question now. We have constructed a special condenser using bakelite as a dielectric which is entirely enclosed and so arranged that air may be circulated through it, and at the same time the relative humidity of the air may be varied. To date all of the tests have been made with clean air (dust-free) and the humidity has been varied from about 40 to 95 per cent. Tests have been made at temperatures ranging from 23 deg. cent. (73 deg. fahr.) to 50 deg. cent. (121 deg. fahr.). In order to keep out the dust a cotton-wool plug is inserted in the air pipe. The value of the applied continuous potential has been varied from 10 to 60 volts per mm. No conduction has been detected with clean air, even at 60 volts per mm., and the following values of relative humidity, 92.5 per cent at 24 deg. cent., 91 per cent at 32 deg. cent., and 90 per cent at 39 deg. cent.

Atmospheric dust in Baltimore contains quite a large percentage of carbon particles, soot, bits of hair, fuzz, dried sputum, bits of dried grass and leaves, etc. One of the next steps in this investigation will be to introduce some dust into the humid air and note its effect upon the conduction.

In an investigation of this character great care must be taken to make sure that any conduction found is not caused by leakage over the insulation or some other unsuspected path, such as a bit of lint.

J. B. Whitehead: I think Dr. Kouwenhoven has not been quite definite in stating his belief in connection with the possible rise in power factor of an air condenser. Generally we haven't a great deal of faith in the suggestion that humidity of the atmosphere can have an effect, or can of itself cause any departure of the power factor of an air condenser from zero value.

Improvements in Insulation for High-Voltage A-C. Generators

BY C. F. HILL¹

Non-member

Synopsis.—A discussion is given of the insulation problem in relation to increased size, rating, and voltages of turbo alternators and some results of experimental studies given showing the possibilities of improving the insulation to take care of such increases.

Mention is made of the effects of high voltage testing and the use of hydrogen on the insulation problem and finally an explanation of a device for the elimination of corona formed around armature coils.

* * * * *

THE present type of turbo alternator is the result of but little more than twenty years development but the changes in such machines have been frequent and impressive. The result is that machines are being built so much larger in size and power output than were considered possible a few years ago that we hesitate to predict the future or place a limit on their size. The same condition may become true for voltages as well. However, when we consider the advance in size and rating we are confronted with the fact that much of the change has been made possible by improvements in mechanical features, an outstanding example being the improvement in the method of removal of heat losses. It is true that the magnetic properties of the iron have been much improved and transposition of strands of conductors has helped to lessen eddy current losses, both being examples of electrical advancement, but as each step in the increase in output per unit was necessary, much of the problem was merely increasing the mechanical size. Yet if we could go back to the time when 5000 kw. was considered a large machine, we certainly would not have expected 150,000 kv-a. without almost revolutionary changes by the electrical engineer as well. The demand continues for larger and larger units, especially larger kw. output, and it is difficult to understand how much advance can be made without some improvement in the electrical features. Therefore, the electrical engineer must look for possible changes, in the magnetic circuit, in the generated currents and voltages, and in the insulation. It is the purpose of this paper to discuss the problem of the insulation engineer from the standpoint of increased voltages especially, with some discussion as to the effects of other developments on insulation, and by means of some experimental results to show some of the limits and possibilities which insulation may impose on further developments of turbine design.

GENERAL DISCUSSION

While further increase in voltage will determine the more difficult problem for the insulation engineer, he

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Presented at Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-19, 1928.

must keep in mind a number of other features which are to be expected in further turbine development. The mere increase in dimension increases the difficulty of insulating the conductor or coil and placing the coils into the slots in good condition. Armature coils are already of the order of 20 ft. in length in the straight part, and the difficulty of making and handling such coils must necessarily increase with length. Of more importance is the matter of temperature, heat dissipation, and efficiency. The insulation problem has always been tied in with that of temperature and heat removal in that the I^2R losses in the conductors must be conducted through the insulation and operating temperatures are actually determined by it. The present A. I. E. E. Standards permit, for armature windings, a maximum rise of 80 deg. based on a total temperature of 125 deg. and most large machines are now designed for an armature winding temperature rise of only 60 deg. Only a radical change in the nature and characteristics of insulating materials will permit designers to raise this limit of temperature rise appreciably.

A new development in the field of heat removal may make itself felt in the near future in the way of using lighter gases such as hydrogen for machine ventilation. A trial of this development is now under way and it will therefore be of interest to consider the relation of this method of ventilation to the insulation problem. The aim, of course, is to get increased output at the same temperature, and from this point of view, no effect will be expected on the insulation so far as temperature is concerned. Lighter gases are better conductors of heat and originally there was some hope that even the insulation itself might become a better heat conductor due to absorbed gases. As a matter of fact, an insulation that is good electrically, does not absorb gases to any extent and the only way in which it will be affected by the hydrogen atmosphere involves corona effects which will be mentioned later.

In the case of armature insulation, the development or changes over the past twenty years have been negligible. As a matter of fact, it can almost be said that the idea of arranging paper, mica, and a bond as we have them now, made possible the modern turbo generator. At first, voltages were relatively low and

machines comparatively easy to insulate. But even as voltage increased from 2500 to 13,000, the insulation engineer was not handicapped. He has merely maintained an increase in thickness of the dielectric to correspond to the voltage rise. In general the situation as regards turbo insulation is satisfactory; it is true, accidental defects may occur, but periodic voltage tests tend to keep service failures at a minimum and the fact that the insulation engineer has not been handicapped seriously in space allowed, has permitted a fairly large factor of safety to be maintained.

We are now at the beginning of a further advance in standard voltages as well as kv-a. rating and size of generating units, and the first increase for many years has been proposed from 13,800 to 22,000 volts. On the basis of previous experience and practise a proportional increase in insulation thickness will take care of this change. This being permitted no particular difficulty arises so far as the insulation itself is concerned except to cut down the rate of removal of heat. But it is highly desirable that the insulation carry more of its share of the load in the way of assuming higher working stresses. This thought is not new as the necessity and importance of higher voltage stresses on the insulation in high-voltage applications is already felt but it does call attention to the need of information on what may be expected in the near future in this respect.

The problem has therefore been attacked from the standpoint of a more severe service on the insulation. The starting point of the study has been the weaknesses of the present insulation with a view of determining necessary improvements within the insulation itself but the problem of what may be done outside the insulation to relieve the situation is also considered. Incidentally the effects of one or two other developments on the insulation problem are mentioned.

MICA FOLIUM UNDER SERVICE CONDITIONS

In order to interpret actual results it will be well to get a clear picture of the insulation studied and the same under service conditions. Mica folium, as it is called, is made of large sheets of paper upon which mica is fastened by means of a bond. The insulation, considered first, is shellac as the bond, holding overlapping mica flakes of two to four sq. in. area. A layer of bond is also placed over the mica surface, and after baking to dryness, the sheet is wrapped around the bar to the desired number of turns and ironed down with heat and pressure until practically a solid insulation is obtained of mica bond and paper. The resultant bars or coils are then wound in the stator slot, a paper slot liner being used to prevent injury to the insulation surface during winding.

Using the shellac bond this insulation has been in use for many years and has given dependable service. Mica of course is a good insulator if it can be held in place and the purpose of the bond and paper is in general to hold the mica although they do have a

considerable insulating value. The chief point to be considered with respect to bond and paper is that they be so chosen that they do not detract too much from the insulating value of the mica.

Service conditions in the machine impose heat, voltage, and mechanical vibration effects. Insulation temperatures having been reduced to approximately 100 deg. cent., satisfactory service is obtained so far as temperature is concerned and in general operating voltage stresses in volts per mil have been kept to values allowing a considerable factor of safety. However, in machines with voltages of the order of 5000 or 6000 from conductor to ground, one voltage effect has developed, that of corona, sufficient in strength to remove all organic material with which it comes in contact. The paper slot lining and paper wrapper of the coil may disappear entirely or at least be found to be eaten away in small spots under the corona arcs. After several years service, however, coils have been examined and no effect found on even the first layer of mica; furthermore, beyond the loss of the paper wrapper, no effect on the dielectric strength has been observed.

One of the defects of mica folium has been the slight tendency to swell. The defect has its good point in that it keeps the coil tight in the slot but it was not known just why it swelled or what other features might be introduced. During the present study, most of the cause of this swelling has been definitely proved to be due to a freeing of a slight amount of solvent vapors which, linked with the fact that the insulation is non-porous and tends to retain the vapors, permits the formation of slight internal pressures. By making a porous insulation the vapors could be allowed to escape but it was felt that this would tend to lower the dielectrical strength somewhat which is undesirable. Further studies as to the effect of the swelling confirmed the prediction that the vapor pockets allowed internal corona² creating an internal power loss of small amount which add two or three deg. cent. to the insulation temperature. This is not serious at operating voltages but tend to increase faster than the voltage so that at higher voltage gradients it would not be desirable. With this information at hand, coils from machines in service have been examined to see if any internal deterioration of the bond could be detected but none was found. The absence of oxygen accounts for this, the concentration of heat in the arcs being evidently too small to do damage by themselves. One possibility of preventing swelling suggests itself in the way of completely removing all the absorbed solvent before winding the coil; dry shellac has excellent properties but it has not been determined if such is feasible as yet. The work has been directed towards obtaining a bond which lends itself readily to obtaining the desired properties more easily.

2. *Gaseous Ionization*, J. L. A. I. E. E., Dec. 1923, also TRANS. A. I. E. E., Vol. XLIII, 1924, p. 116.

POWER LOSSES

In all high-voltage apparatus, an important property of the insulation is that of power losses. By this we have reference to the losses produced by the oscillation of charges within the dielectric itself and manifesting themselves as heat. These have little effect upon the total efficiency of the machine, but although the actual watts lost is not so great, they are concentrated in the dielectric, raising its temperature somewhat. Continued

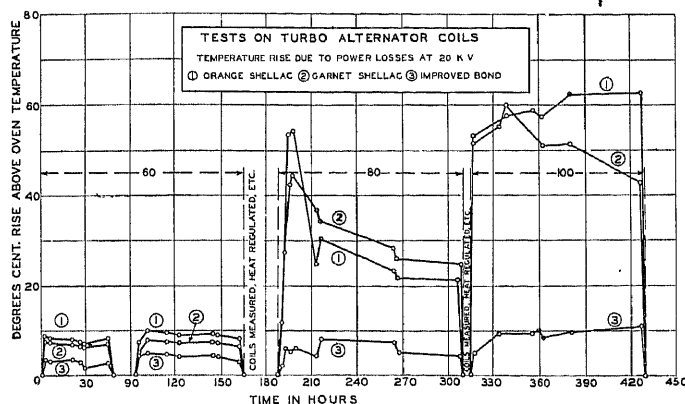


FIG. 1

curing by heating tends to lower these losses by removal of more or less volatile material. Solvents would, therefore, be expected to play an important part in the production of these losses and two possibilities suggest themselves in solving the problem. Either to reduce the solvent to a minimum or to use a solvent which has

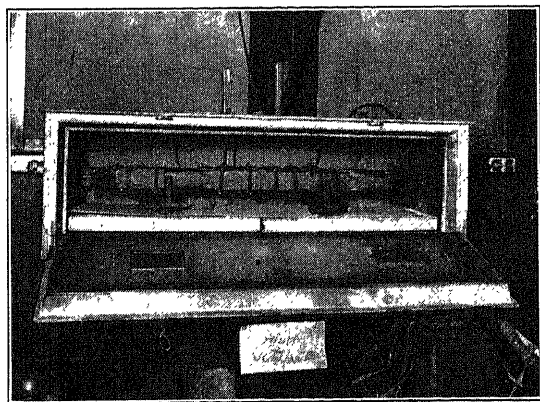


FIG. 2

better dielectric properties in itself, or both. The ideal bond would be one which could be melted and applied at temperatures well above operating temperatures, using no solvent whatever. So far the ideal bond has not been found but results show that a large reduction in losses is possible by a choice of bond, having low losses in itself and soluble in a solvent of low loss, with a reduction of this solvent to a negligible quantity in the finished insulation.

The curves of Fig. 1 show comparative data on standard mica folium with shellac bond and with a bond recently developed along the lines mentioned

above. Since the actual watts loss is of little importance, the temperature rise being of more importance, the temperature rise is used as ordinates in the data. The abscissa is the time in hours that the voltage of 20 kv. is applied to an insulation design for 13,000-volt operation. Attention is called especially to the importance of power losses in case higher voltage stresses are imposed. As a general rule in a 13,000-volt machine, approximately 8000 volts exists across the insulation. More than twice that stress is applied in this case, and it is evident that the losses in the standard folium are too high; on the other hand, the improved bond withstands the voltage readily. Possibly considerably higher temperatures could be used on the latter without sacrificing all the gain over standard folium. The curves also give an idea of the rise in losses with temperature of the insulation.

Fig. 2 is an illustration of the apparatus used in the study of the coils, temperatures being taken by thermocouples inserted in the hollow conductors of the bars. Machine temperatures were imitated by means of a

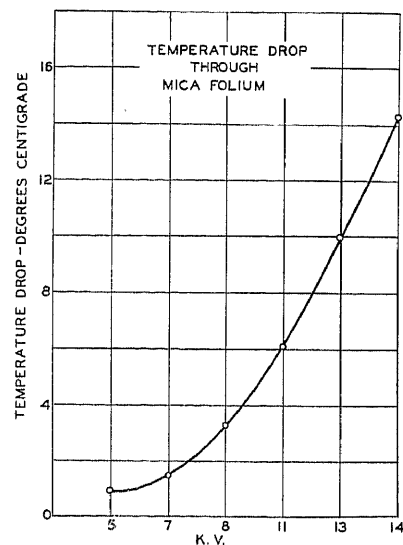


FIG. 3

thermostatically controlled oven and the slots by means of metal clamps. Gaps between clamps give the effect of vent ducts, gaps of one-half in., one in., and seven in. being used.

The curve of Fig. 3 is a characteristic one representing the variation in losses with voltage stress and brings out the fact that the losses increase faster than the voltage. Assuming the equation

$$\text{loss} = E^n$$

n is found to be almost exactly equal to two at 5000 or 6000 volts but increasing gradually to approximately three near the upper end of the curve.

As mentioned above, the swelling of coils due to the solvent is a factor to be considered. Comparative tests on the two bonds in the present case are found in Fig. 4 for a one-half in. gap at 80 and 100 deg. cent. machine

temperature. Curve 1 is for a standard shellac folium while No. 2 is that with the new bond. The processing was done in the shop to make the test comparable. It is evident that considerable progress has been made although even a more complete removal of the solvent may be possible. If the surface layers could be preserved as will be discussed later, and the coil originally wound tightly in the slot, the tendency to remain tight rather than loosen is an advantage. A third variation in the power loss studies involves an effect observed

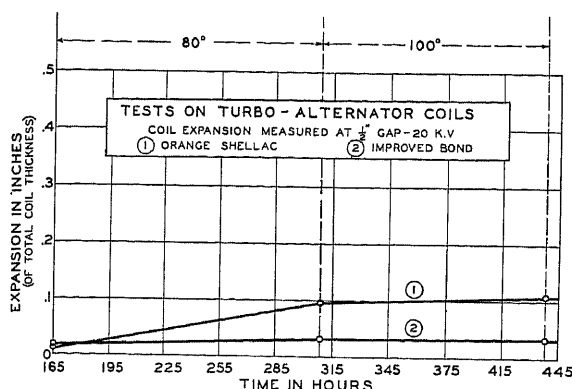


FIG. 4

when high voltages are applied over a period of time at an ambient of room temperature, but between each application of voltage, the coils being given a heat treatment of approximately operating temperatures around 100 deg. cent. The shellac bond is apparently dry when wound on the coils but it was predicted that

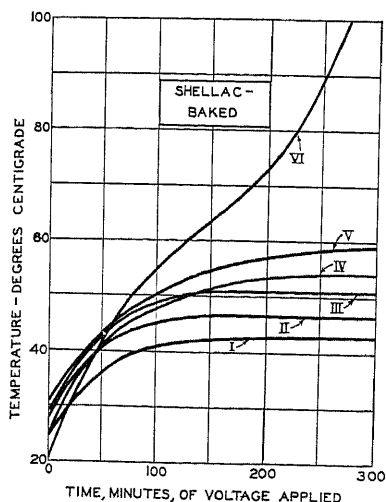


FIG. 5

some solvent is locked up or absorbed and is driven out gradually. The present test is believed to verify this prediction. The voltage used in the present case was 30,000 volts on a 13,000-volt insulation and was applied until temperature equilibrium was obtained in each case.

Figs. 5 and 6 represent standard shellac folium and that of the new bond respectively. It will be noted in

Fig. 6 that baking the coils with the improved bond, no change in loss was obtained, the variation being due to variations in room temperature but in Fig. 5 after each baking, the standard insulation showed increased losses. This was not due to voids as the coils were tightly clamped. Previous to the final curve of Fig. 5, curve VI, this coil was baked about 18 hr. at 115 deg. cent., the temperature-time-voltage curve going up to more than 100 deg. cent. before the test was stopped, and it was evident with the increase of losses with temperature that equilibrium has been passed and breakdown would eventually occur.

Finally the coil with the improved bond was placed in a 100 deg. cent. ambient and 30,000 volts applied until temperature equilibrium was obtained (see Fig. 7). While some curing had probably occurred, the coils were tightly clamped during the test and this effect was believed to be small.

The result of the above experiments are given to show what can be done with insulation of this type, merely by a choice of bond. The data given was obtained for

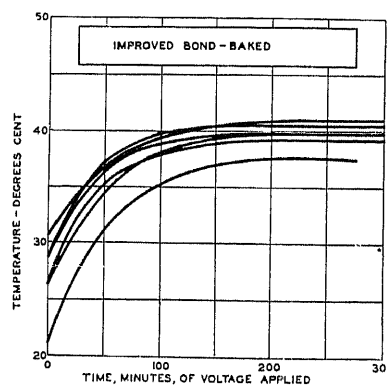


FIG. 6

coils with mixtures of the bond which were as far towards the low loss side as it was convenient to use on account of the high temperatures necessary in manufacture if bonds of lower loss are used. However, such information is important in that it indicates not only possibilities in improving insulation for the present designs of machines, but also for designs when it may be desirable to increase the stress somewhat on the insulation. So far power losses have not been considered in turbine design but we are facing the problem of increased stresses and losses in many high-voltage applications and it is not probable that we shall escape here.

One very important feature of the new bond is the flexibility of the folium as compared to shellac, and it is found possible to use several extra layers of mica which is desirable as long as the coil is good mechanically.

BREAKDOWN TESTS

While it is not intended in this paper to suggest that higher voltage stresses be used until it becomes necessary, it is believed that enough evidence is given

to indicate that the use of increased stresses may be possible and if higher and higher generated voltages become desirable as machines increase in size and output, such may become necessary. As a matter of fact there has been some increase in stresses used during the last several years. A second electrical property of insulation, that of dielectric strength, is of the utmost importance in this connection and it is doubtful if many operating engineers have an idea of the factor of safety maintained in the way of puncture voltages. Just what the factor of safety should be is a different problem but all will agree that with the large valuation involved in a single large generating unit, the factor of safety should be greater than in any other application. The problem of surges alone makes it desirable to know what the actual dielectric strength is and from this point of view, would become still more important for increased stresses. With this in mind, four coils have

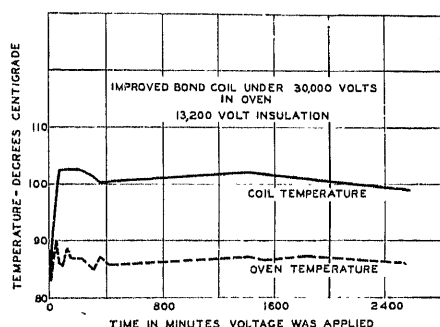


FIG. 7

been tested as follows:—three coils of four ft. length designed for 22,000 volt operation using the improved insulation, were tested by using a six in. layer of tinfoil around the middle of the coil, the whole being immersed in oil. Under a continuous rise voltage test, none of the coils was punctured, all flashing over the surface at values between 150,000 and 170,000 volts. An attempt on a coil of 20 ft. in length in the straight part and three ft. extension on each end; was made in air. This also flashed over on three or four trials at about 165,000 volts. No tests were made on standard shellac folium but no great difference is to be expected on momentary tests although the improved bond will withstand the same voltage longer. It would be of interest to know what the actual puncture values are but the tests obtained were high enough to indicate a sufficiently high factor of safety even for considerably higher operating stresses than are now used. Operating stresses at present are of the order of 30 to 60 volts per mil while the puncture tests indicate values of the order of 500 volts per mil.

TESTING VOLTAGES

A problem which may become more or less acute upon the adoption of higher operating voltage is that of overvoltage tests. It is difficult to get quantitative data upon which to base conclusions but attention is

called to the fact that the effects of voltage vary as E^n where n is of the order two or above and in most cases for test voltages the value of n will be more nearly three. A feature of high testing voltage which has not been experienced up to the present time is that of the disruptive effects of creepage discharges on the surface of coils. Coils may be damaged to the extent of actual puncture of some of the outer layers particularly at a distance of two or three in. beyond the end of the electrode or in the machine beyond the end of the slot. Further studies will be required to determine what voltages should be chosen for tests of this type but an attempted life test on a 13,000-volt insulation using the improved bond and 40,000 volts applied between a metal clamp on the outside of a coil and the conductor, produced an effect which indicates the danger of injuring coils by the application of extremely high voltages. About three in. from the end of the electrode and extending as much as three or four in. farther, the disruptive effect of creepage charges gradually destroyed the paper and bond, loosening and dehydrating the mica so that it exhibited a bushy appearance. Breakdown finally occurred after 1140 hr. in this region while the insulation under the clamps was still in perfect condition. Further tests at 50,000 volts on the same design of coils produced the same effect and caused breakdown in a few hours. It was evident that the rate of deterioration increased rapidly between 40,000 and 50,000 volts. A test of 66,000 volts even for one minute might defeat its own purpose by damaging the surface layers of the coil unless some means of reducing these creepage effects can be devised. As shown in the following paragraphs, the corona and surface creepage effects can be reduced or removed at operating voltages and can be reduced at least, for high testing voltages.

CORONA ELIMINATION IN TURBO STATORS

The phenomenon called corona made its appearance in machines as soon as voltages were developed of the order of 5000 or 6000 volts from conductor to ground. The evidence of its presence is furnished by the odor associated with ozone, which is a product of the action of corona on the oxygen of the air and it is visible to the eye under favorable conditions. While the coil is mechanically tight in the slot, there still exist some very small air-gaps due to manufacturing tolerances and irregularities of the surfaces in contact and these minute gaps are over stressed, producing corona.

So far all evidence points to the fact that the actual danger from corona is slight but there are some reasons why it should be removed if possible, as for example the coil could be held rigidly in the slot without permitting expansion as occurs when the slot liner and wrapper are eaten away. This will also eliminate the uncertainty in the minds of some designers and operators and finally may help to reduce effects of testing voltage. As much as 15 years ago engineers began to feel uneasy about its effects on insulation and the problem of its

elimination was considered. It was evident that all that was necessary was to remove the voltage stress in the air-gap, which could be done by bringing ground potential to the surface of the solid insulation, by making the surface a conductor. Accordingly metallic paints and tinfoil were tried and actually put into some machines. The tinfoil was applied with an outer covering of cotton tape and was grounded at but one point, otherwise the steel laminations would be short circuited. The paints were usually too high in resistance to be efficient. Along with the difficulties of applying and the fact that corona in mica insulated machines without this kind of protection did little damage the problem was dropped as mica was generally used. However, it has seemed more and more desirable to remove the corona if such could be done without too much difficulty and with the possibility of higher generated voltages the problem will become even more important. For this reason the present study has been extended to include the problem.

Some features of a solution of the corona problem are self evident. The conducting film to be placed on the coil must be continuous and adhere to the insulation surface. Further, the resistance of the film must be large enough to prevent eddy currents and in case of grounding at more than one point, should also be high enough to prevent circulating currents. Metallic films in general fall in a class with resistances too low to be used and at best could be grounded at but one point. In case this ground was broken most of the effectiveness of the film might be lost. For this reason a film of high enough resistance to permit of more or less continuous grounding throughout the slot is the ideal. The upper value of resistance is determined by a maximum value which will permit a charging of the condenser between the conductor and film to the full potential of the machine during a half cycle. Calculations show that the resistance per unit length of coil can be as much as a megohm even for relatively few grounding points. On the other hand, a minimum of 1000 or 2000 ohm per in. length of coil is sufficient to eliminate eddy and circulating currents so that a wide range of workable resistance exists.

One special graphitic paint has been found to adopt itself rather readily to the purpose. By controlling the concentration the resistance can be made the order desired and high enough so that continuous grounding can be used if necessary. It is not improbable that a number of materials can be found which have the proper characteristics but the one mentioned seems to have most of the desirable properties in case a smooth surface is furnished for its application. A problem, concerning which there is some uncertainty as yet, is that of the life of the film at the vent ducts under the action of the high velocity air currents used in cooling the machine. To avoid the possible destruction of the film at this point, the film can be protected by retaining the fish paper slot liner, perforating this paper layer

at points between each vent duct along the side of the coil and painting over the hole on both sides with the same graphitic paint so that the film also covers the edge of the paper in the perforation. This has been shown to give perfect grounding and since the paper lining of the slot is protected from the corona it should protect the film over a long period of the life of the insulation.

The conducting film (See Fig. 10) just discussed removes the corona throughout the slot but at the end of the slot corona occurs which gradually tends to eat away the film itself. Furthermore, this corona will of course tend to destroy the organic material on the surface of the coil and must be eliminated before the device is complete. Burying the end of the film deep in a solid insulation suggests itself as a means of eliminating this defect, but the space available is small between the coils and needed for ventilation purposes. Two other methods have also been suggested and one

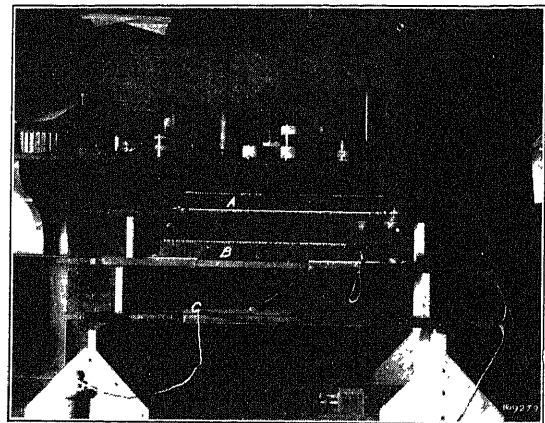


FIG. 8

will be given which has been perfected to the point where it is believed to be practical.

If an extension of the conducting layer is made a few inches beyond the slot, a capacity current flows along this extension charging up the condenser between the layer and the conductor. The capacity, of course, is small, being of the order of $15 \mu\mu\text{f.}$ per in. length of coil, and the currents flowing are also small, decreasing towards the end of the extension. Calculation shows however, that if resistances of the order of 100 megohms per in. length of coil could be found the IR drop along this extension could be made to take care of most of the voltage difference between the conductor and ground so that at the end of the extension, the voltage is too low to ionize the air, thus removing the corona completely. Dependable materials giving the desired resistance have been found available and some idea of the effectiveness of the device is obtained from Fig. 8. A represents the corona between a laminated structure and coil at 30,000 volts applied with no attempt at elimination, B shows the effect of the graphitic layer under the same conditions with the end effect, which is later eliminated

in C . It is possible to damp out 30,000 volts with a minimum of approximately a five in. extension; 8000 volts can be taken care of with approximately a two in. extension, leaving the drop at the end below the corona point.

The accurate solution of the problem involved in the extension is a particular solution of the transmission line equation for parallel conductors with uniformly distributed resistance and capacity, the differential equation being

$$\frac{\partial^2 E}{\partial x^2} = C R \frac{\partial E}{\partial t}$$

The inductance is considered negligible.

The solution of this equation may be found in engi-

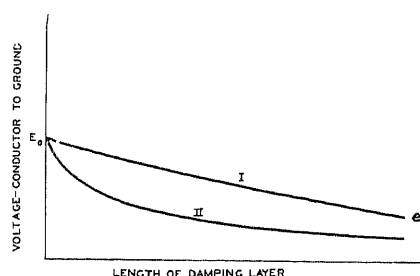


FIG. 9

neering texts but for practical purposes the order of magnitude of the resistance can be obtained from the approximate equation

$$r = \frac{2(E_0 - e)}{C \pi f l^2 10^{-12} E_0}$$

Here r is the resistance per unit length, E_0 the applied voltage, e the residual voltage at the end of the extension, C the capacity per unit length, l the length of the extension, and f the frequency. For lengths, permissible in practise, the value of r is found to be of the order of 100 megohms per in. length of coil. The values actually used are approximately 500 megohms per in. as measured by a 1000 volt megger. The resistance of materials of the type available vary with voltage of course, and are somewhat lower under machine voltages.

A feature of the damping resistance or extension which may be of interest is represented in Fig. 9. In order to get a uniform drop in voltage per inch of extension, curve I , which is the ideal way, the resistance per unit length would be required to vary inversely as curve II of the Figure. This is impossible in practise where the resistance is constant per unit length so that the voltage drops off more nearly as curve II .

In building the extension it has been found necessary to use a porous material to hold the resistance material and a special asbestos tape with the organic filler burned out. It has been possible to do this without losing much of the mechanical strength of the tape and some of this loss is regained when fastened to the coil surface with a bond. The tape is then filled with the high resistance material and electrical connection made

with the graphitic layer, Fig. 10 shows the complete assembly.

CORONA IN END WINDINGS

A problem which has caused some discussion in the past has to do with the formation of corona on the metal parts of the structure bracing the end windings. So far this problem has not been of much importance for the type of bracing used with mica folium coils, as enough insulation could be used between the metal parts and the coils, that operating voltages could produce only a soft, harmless corona at most. The question may be revived, however, with voltage increases in machines, but the problem in any case can not be considered serious since types of bracing can be used in which extra insulation can be added to bring the stresses in the air-gap below the corona point. It is a simple matter to calculate the air-gap stresses on the basis of the insulation thickness and dielectric constants or in other words, to calculate the insulation thickness necessary. The metal parts in such cases are to be assumed to be at ground potential, that is, at the average of the coil potentials, thus insuring that no high voltages are built up across the insulation at any point. From this point of view it is necessary to ground all metal parts, but in general this is more important in that it permits better mechanical features.

Reference was made above to the effects on insulation of corona in hydrogen. The usual deterioration of

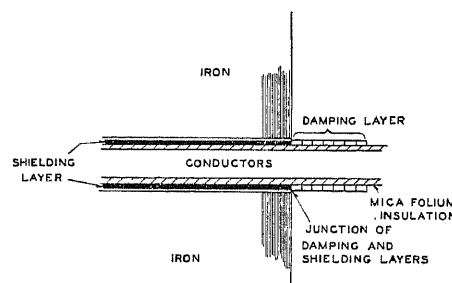


FIG. 10

organic material in the presence of air under corona is due chiefly to oxidation. With hydrogen this effect will be absent³ and the bad effects usually associated with corona should disappear as long as the arc temperatures are not too high where they actually strike the insulation. Even intense corona has been found to have but slow effect under short tests of a few weeks.

For the same reason, the absence of oxygen protects laminated insulation from internal corona.

SUMMARY

A summary of the above discussion may be made as follows:

1. That as generated voltages are increased it may become necessary to use higher voltage stresses in volts per mil thickness of the insulation, which in turn

3. Knowlton, Rice, and Freiburghouse, *Hydrogen as a Cooling Medium for Electrical Machinery*, TRANS. A. I. E. E., Vol. XLIV, 1925, p. 922.

may necessitate the use of a lower power factor material in order that excessive heating be avoided.

2. That a very decided improvement in this property can be obtained for mica folium by a choice of bond containing only a negligible amount of a low loss solvent or other volatile material.

3. That the reduction of the solvent decreases the tendency of such coils to expand, and it has been found that the swelling is reduced to a small fraction of that of older insulations.

4. That the factor of safety to puncture as determined by continuous rise voltage tests is considerably more than is ordinarily considered necessary for most applications and that the results indicate higher stresses on mica folium could be used.

5. That so far the effects of corona have not been serious and in no case has the mica been affected, yet to protect the organic surface of the coil, it may be desirable to eliminate corona at present voltages as well as at higher voltages. In hydrogen it will not be so important.

6. That a method of eliminating corona on armature coils has been devised which is believed to be practical.

Discussion

P. L. Alger: Mr. Hill has given us a very interesting and suggestive article, which I am sure will be a valuable contribution to the literature. Mr. Hill evidently believes, and I fully agree with him, that the whole subject of insulation of armature coils hinges on two points, the first being the choice of the sticker to hold the mica together, and the second being how to avoid corona discharges.

Any sticker used must be not only a good insulator, heat resistant, and acid resistant, but it must also be so flexible that it can be applied, and the coil can be handled and taken out of the machine and put back without damage, while at the same time it must have so high a boiling point or melting point that it will not flow under operating temperatures. In cables, flowing is permitted because the insulating material is held by a sheath, but in an armature coil this is not possible. Since any material like varnish is inherently flexible, if it has a low boiling point, and brittle if it has a high boiling point, these two requirements of flexibility and high temperature resistance are incompatible, and it is very difficult to strike a balance between the two. As Mr. Hill has said, shellac is all right at low temperatures, but when heated it loses alcohol and becomes very brittle. We have found that black asphalt varnishes give the best results, partly because they contain many ingredients of slightly different boiling points, so that by aging them to any desired degree, the boiling point can be raised just enough to avoid swelling in operation, while at the same time the maximum of flexibility is secured.

In regard to the corona question, it is interesting to think at how low a voltage corona occurs in armature coils. The dielectric constant of mica insulation is about 3 in magnitude, which means that the air in series with the insulation is subjected to a stress about three times as great as that in the insulation itself. This, coupled with the fact that the external air spaces are irregular, gives actual maximum stresses at certain points in the air surrounding the coil, of five or six times that in the insulation and therefore, external corona begins at very low voltages—as a matter of fact, at about 3000 or 4000 volts on a 22,000-volt coil. It is, therefore, very difficult to avoid it completely. We have found that, by using simple asbestos tape armor on the outside of the coil, good results are obtained. Asbestos is sufficiently conducting to hold down the potential of the coil surface near the embedded parts below the sparking voltages.

Great variations in surface conductivity occur with changes in humidity, with dust, and with the type of varnish coating employed on the end windings, but in general values of surface resistivity of the order of 50 megohms per in. of perimeter per in. length of coil give good results. The accumulation of dust on the end windings of machines in service acts initially as corona protection, thus accounting for the diminution of ozone often noticed after machines have operated for some time. Too much dirt, however, lowers the surface resistivity too greatly, causing increased discharges.

Fortunately, corona can be permitted without giving much operating trouble, as shown by the fact that two 22,000-volt synchronous condensers have been operating in India for the past five years without any corona protection whatever, but with insulation consisting of mica tape and black asphalt varnishes around the entire coil. These machines have so much corona on the end windings that the lines between the terminal coils of each phase and the adjacent end windings of the next phase are continually illuminated by a line of light during operation. In spite of this, they have operated for five years without noticeable deterioration. Thus, while external corona is of great importance, especially in high-potential tests, it is not really a thing to be regarded as a source of danger to mica-insulated machines in normal operating conditions.

S. L. Henderson: I was very glad to have confirmation from Mr. Alger of so much of the material that was in Mr. Hill's paper. It has been very interesting to me, as a machine designer, to realize that the problems of cable manufacture are much the same as we have in our insulations. We are bothered with moisture and voids in the insulations and have the problem of porosity in the paper. We can pick a paper that is low in moisture but too brittle to use, and we are working between the same limits. We are also trying to reach the same solution of finding an insulation that will remain through its life practically as good as the day it was made.

C. F. Hill: I was much interested in Mr. Alger's remarks and note in particular that his experiences in general are similar to our own. One point in particular, involving the use of asbestos tape armor, is of especial interest. We have found that asbestos tape at room temperature takes up moisture until it is sufficiently conducting to make a fairly good shield over a coil surface and have found that it is especially valuable on coils at room temperatures when high-voltage testing is done as it tends to prevent static discharges over the surface which might mar the surface layers of the coil. Asbestos, however, is a rather good insulator when dry as in a hot machine and our experience has been that it then does not eliminate corona. We have also found it desirable to bake out the organic filler of asbestos tape before applying to the coil in order to insure that static discharges under high-voltage testing may not burn conducting paths through the tape. This is especially necessary, for example, in the case of 22,000-volt insulation when applying up to 70,000 and 80,000 volts.

Mr. Alger's remarks on corona in operating machines are in general agreement with our experiences. In the slot, however, corona will attack all exposed organic material and it is to preserve the surface that corona eliminators are applied and then only for higher voltage operation. As to the choice of bond used, any bond must be a compromise of properties and for extremely high-voltage operation the electrical properties must assume an important role. An attempt was made in the paper to give a complete picture of the requirements for turbo coil insulation and to give an idea of what could be done in the way of approaching, at least, a good insulation. Shellac from alcohol solution is at a disadvantage in some respects. On the other hand, shellac with the alcohol omitted entirely can be made with excellent properties, far better mechanically than asphaltic bonds, but difficult to process at present into this type of insulation. We believe that the low-loss characteristic of asphaltic bond gives it some advantage as yet for high-voltage operation.

The Gould Street Generating Station of the Consolidated Gas, Electric Light and Power Company

BY A. S. LOIZEAUX¹

Associate, A. I. E. E.

Synopsis.—The paper is descriptive of the Gould St. Plant. Pulverized coal is prepared in a separate building. Only one boiler is provided per turbine, each boiler delivering a maximum of 520,000 pounds of steam per hour. Automatic control is provided for the electric drive of boiler auxiliaries, electric auxiliaries being used throughout the plant. 250 volt exciter and 480 volt house turbine

are on main generator shaft. Switch house is of isolated phase construction with vertical operation of switches. Actual costs are given for the first unit, with estimated costs for completed plant, resulting in costs for the completed plant of \$88 per kw. for normal output and \$80 per kw. for maximum output.

* * * * *

THE new Gould Street Plant which began operation in January, 1927, is located in the City of Baltimore on the Patapsco River, an arm of the Chesapeake Bay. This waterfront site was formerly the power plant location of the Baltimore Electric Company which had been purchased by the Consolidated Company in 1908, and has not been in operation since 1918. The comparison between the old plant and the new illustrates the great advance in the art of electric power generation during a period of 20 years, the new units having twelve times the capacity of the old, with a coal rate of the new plant less than one-half that of the old plant.

From the standpoint of nearness to important load

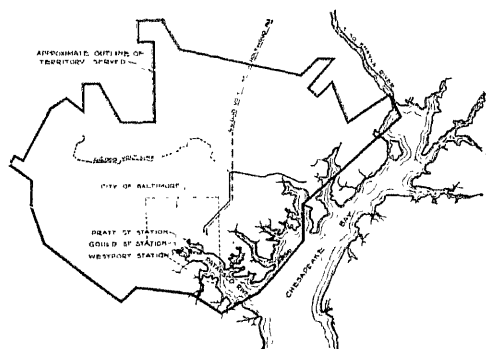


FIG. 1—TERRITORY SERVED BY THE CONSOLIDATED GAS, ELECTRIC LIGHT & POWER CO. SYSTEM

centers the site is highly desirable so that the energy is distributed by underground cable at 13,200 volts without transformation. The plot measures 405 ft. by 635 ft. and is of sufficient size to supply load growth for perhaps 10 years, when the progress of the art of power generation will probably make it desirable to begin anew in another location with higher pressures, higher temperatures, and, perhaps, a materially different heat cycle.

1. Electrical Engineer, Consolidated Gas, Electric Light & Power Co., Baltimore, Md.

Presented at the Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-19, 1928.

SOURCES OF POWER IN BALTIMORE

The accompanying map, Fig. 1, shows the territory served by the Baltimore plants and indicates the city limits and the location of the Westport and Gould St. plants; also the former railways plant at Pratt St.

The Westport plant began operation in 1905 and provided for growth of load through 1926, a period of 21 years. Westport has a 25-cycle capacity of 125,000 kw. and 60-cycle capacity of 40,000 kw.

The Pratt St. plant was formerly a railway generating station but now contains only one standby unit of 20,000-kw. capacity.

HYDRO ENERGY

A considerable part of the electric energy used in Baltimore comes from the Holtwood plant of the Pennsylvania Water and Power Co. The Holtwood plant is located on the Susquehanna River at Holtwood, Pennsylvania, and consists of a hydroelectric plant with 87,000 kw. in 25-cycle capacity and 24,000 kw. in 60-cycle capacity. There is also a steam station at Holtwood of 25,000-kw., 60-cycle capacity. The transmission lines from Holtwood to Baltimore are 25-cycle, 66,000-volt, 40 mi. long.

GOULD STREET GENERATING CAPACITY

Gould St. has one 36,000-kw. unit operating and a second duplicate unit which will begin operation in April, 1928. The plant is designed for four 36,000-kw. units, a total of 144,000 kw. at 60 cycles.

ARRANGEMENT OF PLANT

The general view in Fig. 2 shows the arrangement of the plant, the power house being built on the water's edge. The coal unloading tower is placed about the center of the bulkhead line. Coal is transported by belts to the pulverizing plant. The buildings of the former generating plant were used, the old boiler house being transformed into a pulverizing plant and the old turbine room into a service building and machine shop. The switch house is a new building on the north end of the property toward the city, the power station and switch house being connected by underground concrete tunnels.

FOUNDATIONS

The waterfront end of the site was reclaimed from the river by filling in. The land adjacent to the power plant is to be a city pier, providing a ship channel 35 ft. in depth. These conditions made it necessary to use reinforced concrete caissons to support the end of the plant abutting on the water. Fig. 3 shows a plan of foundations. The caissons are eight in number, some circular and some oval, and are sunk to a depth of 40 ft. to a bottom of gravel and stiff clay. This con-

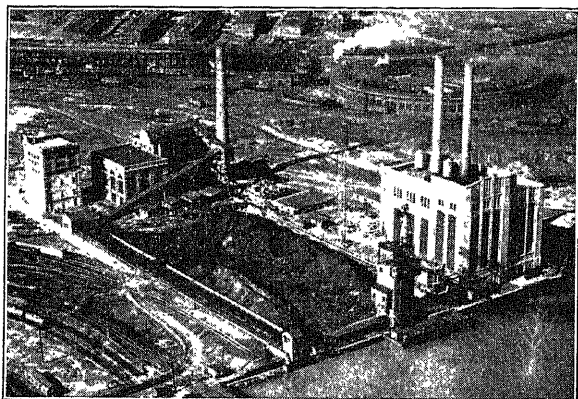


FIG. 2—AERIAL VIEW OF GENERATING STATION

struction insures that the 35-ft. deep channel will never threaten the stability of the power house.

The coal unloading tower rests on two oblong caissons sunk to a depth of 70 ft. The forms for these caissons were built of timber and steel and launched like boats and sunk into place, the open method of sinking used to 50 ft., and the compressed air method, from 50 ft. to completion. A third caisson is provided to support an

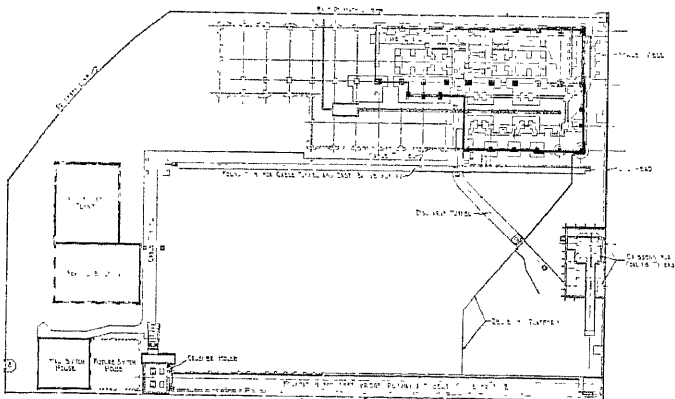


FIG. 3—FOUNDATION PLAN FOR BUILDINGS, COAL HANDLING EQUIPMENT, AND COAL STORAGE

additional or twin coaling tower that will be required for the completed plant.

The waterfront end of the coal field rests on a relieving platform in order to prevent the weight of coal from moving the soft underlying material. This relieving platform rests on wooden piles driven on 3-ft. 8-in. centers and consists of a reinforced concrete slab

18-in. thick and good for a load of 2630 lb. per sq. ft., making it safe to store coal 40 ft. deep over the area.

Other foundations for buildings, runways for coaling bridge, and foundations for turbines are all supported by wooden piling, capped with reinforced concrete mats. The mat for the turbine foundation is 3 ft. thick and is isolated from other building foundations.

COAL SUPPLY

The coal used in Baltimore power houses comes from upper West Virginia and central Pennsylvania coal fields, over three railroad systems. A differential of 25 cents per gross ton exists in favor of water delivery of coal as compared with rail delivery. The result of this differential is that in all of the three plants coal is received by water delivery.

The company maintains its own fleet of two steam tugs and nine coal scows to transport coal from the

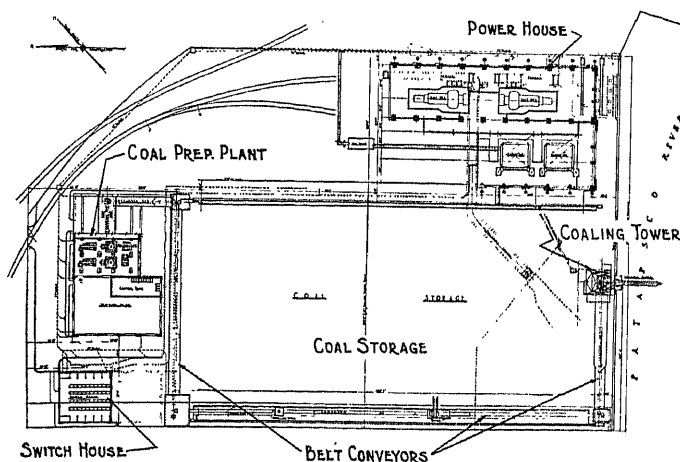


FIG. 4—GENERAL PLAN OF STATION SHOWING POWER HOUSE, SWITCH HOUSE, COAL PREPARATION PLANT, COAL HANDLING EQUIPMENT, AND STORAGE LOT

unloading piers of the railroads to the waterfront unloading equipment at the several stations.

During the year 1927, the Baltimore plants consumed 301,666 short tons of coal, the average analysis being 14,090 B. t. u. and an ash content average of 8.27 per cent.

COAL HANDLING

At the Westport Plant, there are two unloading towers, both electrically operated, and an aerial cable for stocking out and reclaiming coal, the maximum stock of coal on the lot at one time being 76,025 tons.

At Gould St. the coal field is designed for a traveling bridge and the lot will hold 70,000 tons when stored to a depth of 40 ft. Fig. 4 is a general plan of the station and shows the coal handling equipment and coal storage lot.

Coal is unloaded by an electrically-operated tower with Mead Morrison equipment and a two-ton bucket, the present tower having an all-day capacity of 165 tons per hour. The future Twin tower will increase

the capacity to 300 tons per hour. The coal, after being unloaded in the tower hopper, is received by a Bradford breaker 12 ft. by 19 ft. This breaker reduces the coal to a maximum size of $1\frac{1}{4}$ in. and removes trash, delivering such material through a chute to an outside location.

BELT CONVEYERS

The belt conveyor system consists of five belts with two trippers. The first conveyor receives coal from the hopper under the breaker in the coaling tower and travels parallel to the bulkhead to the southwest corner of the lot, where it delivers coal to conveyor No. 2. This belt carries the coal along the western side of the field and either stocks the coal out in the field by means of a tripper, or delivers it to a secondary crusher.

The secondary crusher is installed in a concrete pit at the junction of No. 2 and No. 3 belts and receives coal by gravity from conveyor No. 2. This crusher is a hammer mill of steel plate construction built by the Pennsylvania Crusher Co. It is rated at 200 tons per hour but can handle 400 tons of dry friable coal.

No. 3 conveyor carries the coal along the northern

provided so that in the event of trouble on any belt all preceding equipment including apron feeder and breaker will be immediately stopped preventing an accumulation of coal at the junction points.

The belts are arranged so that any one of three operations may take place; *viz.*, tower to preparation plant bunkers, tower to storage, or storage to bunkers. The motors for these conveyor belts, five in number, are controlled by push buttons which operate single-step primary resistance starters, the resistance being cut out by the operation of a small motor driven definite time relay.

STORAGE AND RECLAIMING EQUIPMENT

At the present time coal is being stocked out and reclaimed by a gasoline engine driven, crawler crane, equipped with a one-yard grab bucket. The capacity of this rig is about 60 tons per hour.

When the third generating unit is installed, it will be necessary to purchase the traveling bridge. The runways for the bridge are in place, since the concrete work was so intimately connected with the supports for No. 2 conveyor on the west side and the cable tunnels on the east side, it was economical to pour them while the concrete plant was set up.

COAL WEIGHING AND SAMPLING

Two Merrick weightometers are used to weigh the coal in transit. One is installed on No. 1 conveyor and weighs all coal received at the plant. A second is located on No. 4 conveyor and gives a record of the coal sent to the preparation plant bunkers.

A Dings magnetic pulley is used at the head of No. 4 conveyor. It serves to prevent any magnetic material from getting into the bunkers above the pulverizing mills. This gives triple protection since the Bradford breaker removes the larger pieces of foreign material from the coal, the hammer mill is equipped with tramp iron pockets which catch a part of the foreign material and the magnetic pulley throws out the nails, small bolts, etc., that remain.

An automatic coal sampling device is now being installed at the junction of conveyers No. 1 and No. 2. It consists of a rocker shaft carrying several 4-in. tubes for collecting the gross sample, and a Sturtevant motor driven sample crusher and splitter. It is arranged to run whenever No. 1 conveyor is in operation, and does not require a separate control. The gross sample taken by the tubes will average one pound per ton and will be taken simultaneously at several points in the ribbon of coal as it leaves the head pulley of the conveyor. This gross sample will be crushed and split so that a sample of about two pounds per hundred tons will be collected for the laboratory while the discard will run by gravity onto No. 2 belt and pass on with the other coal.

COAL PREPARATION PLANT

The general arrangement of the coal preparation plant is shown in Fig. 5. The building was originally

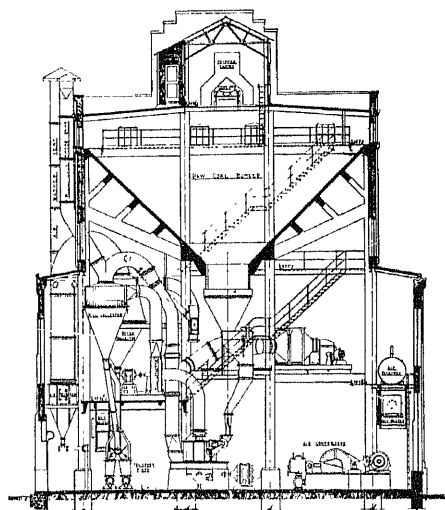


FIG. 5—CROSS-SECTION OF COAL PREPARATION PLANT

edge of the field. It is inclined at an angle of 19 deg., and lifts the coal 77 ft. from the pit under the hammer mill to the No. 4 conveyor, which carries the coal into the end of the preparation plant above the bunkers. No. 4 conveyor is also inclined 19 deg. and lifts the coal 24 ft.

No. 5 conveyor distributes the coal in the raw coal bunkers by means of a traveling tripper.

All of the conveyers are equipped with 36 in. rubber belts and have a capacity of 336 tons per hour. There is no speed adjustment on any of the belts; the ribbon principle is used, the rate of feed or thickness of ribbon of coal is regulated by the apron feeder which delivers coal to the Bradford breaker. The flow is continuous from this point until the coal is delivered to the preparation plant bunkers. A similar regulation is provided at the traveling hopper above No. 2 conveyor when coal is reclaimed from storage. Electrical interlocks are

the boiler house of the former plant. All but two of the original boilers were removed, the two remaining boilers being used to supply steam during the construction period. The building required considerable alteration including the removal of the old coal bunkers and the installation of new bunkers with increased slope so that the coal would flow to the discharge gates at the bottom of the bunkers, the capacity of the bunkers being approximately 900 tons. The coal gates at the bottom of the bunkers control the flow of coal to Richardson automatic scales now being installed. There are two scales for each mill. From the discharge hopper of the Richardson scales the coal flows to two feeders for each mill. The original installation included steam driers but these have been replaced by the system of drying in the mill. Air from a tubular air heater using steam at boiler pressure is blown into the circulating air as it enters the mill providing hot dry air to absorb moisture from the coal in the mill. Sufficient air is bled off from the top of the cyclone to discharge the moisture picked up and keep the humidity of the air in the circulating system below the dew point. This air bled off is replaced by heated air coming from the air heater which is mixed with the re-circulating air before it enters the mill. The cyclones in which the air and coal are separated discharge the coal into the hoppers above the coal transport pumps. The air drawn off from the circulating system passes through a concentrator, in which the heavier solids are removed, and from there it passes through a washer before being vented to the atmosphere. This washer is of the vertical type, in which the gases are washed by steam and water sprays.

The machinery for preparing and transporting the coal comprises two 20-ton Raymond roller mills, each with a separate exhaustor and circulating system and steam air heater; two transport pumps, each having a nominal rate of capacity of 40 tons per hour, and two 735-cu. ft. two-stage motor driven air compressors.

The construction within the mill house is such that wherever possible, ledges, or resting places for coal dust have been avoided. As two of the old boilers were left in service for furnishing construction steam, a cinder block wall was built to separate the grinding room from that section of the old building where the boilers remain. Sash in the preparation plant opens outward and is of the plain glass type, providing a 10 per cent area of plain glass, as prescribed by the underwriters.

All of the equipment in the preparation plant is electrically driven, using 440-volt, three-phase, 60-cycle, squirrel-cage type motors. There are no circuit interrupting devices in the preparation plant. Motors are controlled from water-tight push buttons operating contactors which are located in a control room, which is located in the turbine room of the old plant. Sequence interlocks are provided on the controls to prevent stopping equipment in incorrect order and consequent flooding or jamming of the coal feeding system. Small

motors are thrown directly across the line, but the motors for the mills, mill exhausters, dryer exhaustor, transport pumps, and air compressors are started by primary resistance type contactor control. Resistance grids are in the control room. Lead covered wire and cable are used for the power circuits. Control buttons are mounted adjacent to each piece of apparatus and also on a control board. The operator in charge of the grinding also controls from this board the switching valves in the coal lines over the bunkers in the boiler house.

COAL TRANSPORT LINES AND COAL BUNKERS

Coal is pulverized in the mills so that 70 per cent will pass through a 200 mesh screen. After collection in the cyclones, pulverized coal enters the transport pumps and in combination with compressed air is transported through 6 in. pipe lines about 750 ft. long to the bunkers in the power house. The transport pumps and pipe lines are in duplicate and are so arranged that either pump can handle the output of either or both mills. The two boiler bunkers may be fed by either of the transport lines, selection being obtained by electrically operated transport valves located over the bunkers and controlled from the preparation plant master panel. Paralleling the transport lines is a 1½-in. line with connections to each for purging them with compressed air. The coal level in the bunkers is indicated on individual boiler control panels and also on the preparation plant master panel. A specially developed device takes periodic "soundings" in the bunkers and operates Selsyn transmitters for this service. Two high level paddles are also installed in each bunker to give a flashing lamp indication when the bunkers are nearly full.

The powdered fuel bunkers are each 100 ton, V-shaped, structural steel, insulated on the outside to prevent condensation inside the bunker. All parts of the bunkers are welded and tested water-tight.

CROSS-SECTION OF POWER HOUSE

Fig. 6 is a cross-section of the power house showing a rather compact arrangement of equipment, yet providing ample space for operation. Abundant natural light and ventilation is provided for both turbine room and boiler room. A pipe gallery provides for longitudinal runs of pipes. The electrical gallery is open to the turbine room and on the same level as the turbine floor giving easy access to electrical operation.

COAL FEEDERS

The coal is fed by four quadruplex screw feeders per boiler to sixteen Lopulco type burners through 6-in. pipes crisscrossed to prevent stratification in the furnace in the event of outage of one or more feeder groups.

FURNACE

Three sides of the furnace are water-cooled by fin-tube surface backed by special tile, rock wool insulation and steel casing. The front wall is of firebrick, cooled

by the preheated secondary air, admitted to the furnace through ports at sixteen levels in this wall. A water screen interconnected with the rear wall circulating system protects the inclined floor of the furnace which forms the ash hopper.

AIR SUPPLY AND GAS REMOVAL

Primary air, used to convey powdered fuel from the

directly ahead of a C-type plate preheater mounted above the gas outlet of the boiler.

Tertiary air is taken from the secondary air duct for admission around the burners.

The gases leaving the preheater are removed by two induced draft fans and discharged into an eleven-ft. diameter self-supporting unlined steel stack, one per boiler, extending 213 ft. above the burner arch.

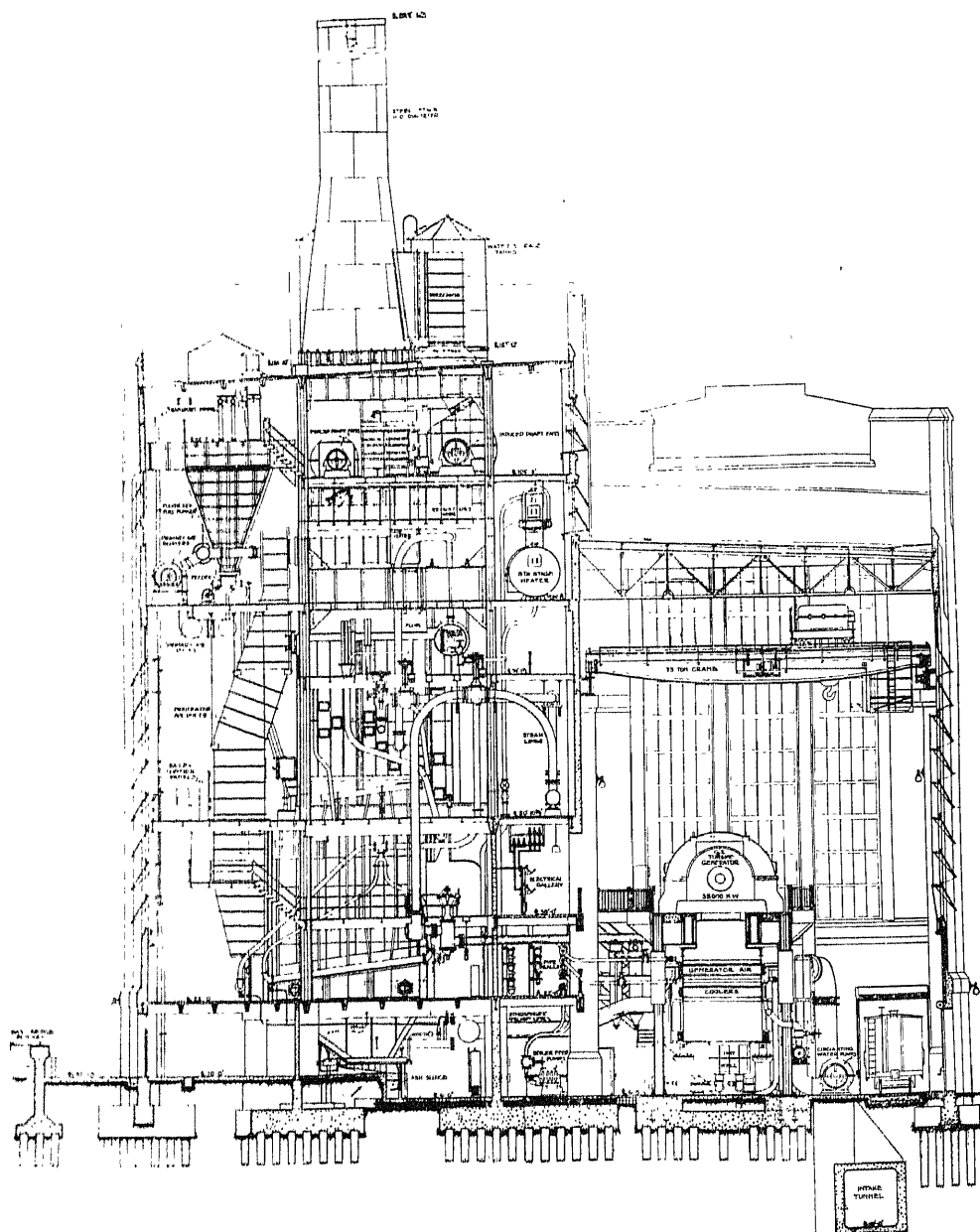


FIG. 6—CROSS-SECTION OF TURBINE ROOM AND BOILER HOUSE

screw feeders to the burners, is a mixture of preheated air tapped from the secondary duct and tempered with room air. Primary air is supplied by two fans per boiler, connected on the discharge by an air bus, which makes any fan available for either boiler. Two forced draft fans per boiler furnish the secondary air taken from the room and discharged into a plenum chamber

BOILER

The use of one boiler for a 36,000-kw. turbine with only one additional boiler as a spare unit marks an advance in plant design. Each steam generating unit has a maximum output of 520,000 lb. per hour at 450 lb. drum pressure and 725 deg. fahr. superheater outlet temperature, which is sufficient for about 46,000

kw. turbine capacity. Reserve capacity gained by increased size of boiler auxiliaries even at some sacrifice in normal operating economy, was found to be more economical than the addition of spare boiler units. Four turbines will ultimately be supplied by five boilers. Fig. 7 is a section of boiler and furnace.

Several features in the design of the boiler, a conventional B & W cross drum steel encased type, were

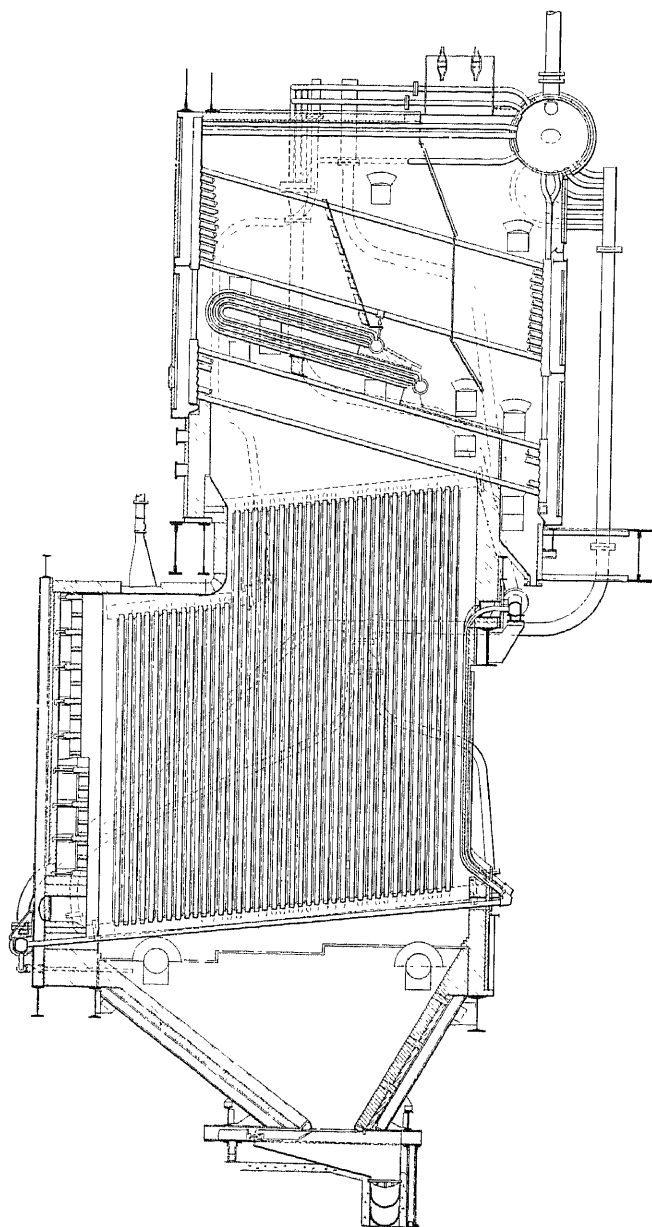


FIG. 7—CROSS-SECTION OF BOILER AND FURNACE

unique. It was the first boiler at 450 lb. pressure to have 4-in. tubes. A considerable increase in heating surface was gained at small expense by extension of tube length from 22 ft. to 24 ft. Modifications in the manufacturer's previous design allowed an advance from 385 pounds to 450 pounds operating pressure. The drum diameter, 60-in., was the largest attempted for that pressure at that time, and the length of 34 ft.

was the greatest that the manufacturer could furnish without a girth seam. Two steam outlets were insisted upon. General Electric steam flow meters modified for use as water level indicators and recorders are installed at the operating floor level.

SUPERHEATER

The superheater is of three-pass hair pin loop construction of the interdeck type and is located between the 5th and 6th rows of boiler tubes. To avoid excessive pressure drop at the higher ratings and a consequent decrease in turbine capacity, the diameter of the manifolds was increased considerably over the original design. Calculations showed that the larger manifolds would be a profitable investment.

ASH REMOVAL SYSTEM

Ash leaving the combustion chamber falls through the water screen which protects the furnace floor, and

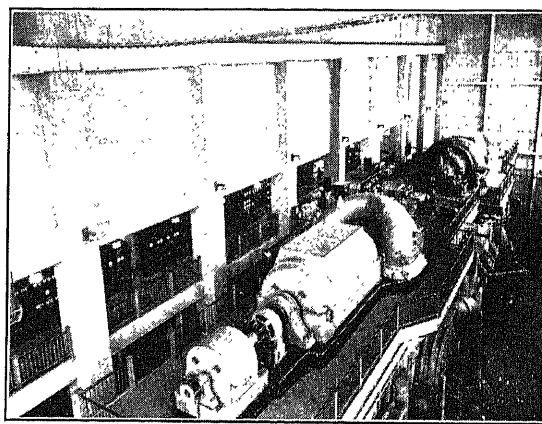


FIG. 8—VIEW OF TURBINE ROOM SHOWING NO. 1 AND NO. 2 UNITS

collects in the ash pit hopper which is lined with fire brick and has a capacity of 4000 cu. ft.

Three horizontal, hydraulically operated ash gates are provided on the bottom of the ash hopper for each boiler. Those gates, when opened, allow the ash to drop on inclined feed plates from which it is washed into the main sluice by jets of water.

Large clinkers are retained on a grizzly over the sluice and are broken up with a sledge after the ash gate is closed. The ash is transported in the sluice by water admitted at intervals through high velocity jets to a temporary ash settling pit outside of the boiler house. The settling pit is 12 by 28 by 21 ft. deep with sides of steel sheet piling and is provided with adjustable baffles to assist in settling the fine ash. An overflow is provided for the water which discharges to the sewer. The ash is removed by a clamshell bucket on a crawler crane, loaded into trucks, and hauled to the ash dump.

TURBO GENERATOR

Fig. 8 gives a view of No. 1 unit in the foreground, and unit No. 2, under construction, in the background. The alternator is a 43,750 kv-a., 80 per cent power

factor, 1876 rev. per min., 13,200 volts., three-phase, 62½ cycle machine, which is designed to operate later at 60 cycles. In addition to the main generator there is a shunt-wound shaft exciter rated at 250 kw., 250 volts d-c. overhung on the main shaft and beyond this and connected by means of a Fast flexible coupling is an auxiliary generator having a capacity of 1500 kv-a. at 80 per cent power factor and 460 volts, three-phase, 62½ cycle. The overall length of the turbo generator unit is 69 ft.

The turbine is a 13-stage Rateau impulse machine of 36,000 kw. capacity and drives the main generator through a Fast flexible coupling. It is a modified form of a turbine of lower normal rating of the non-bleeding type. The initial stages, however, have been opened up to pass the additional steam used in bleeding. Steam is supplied at a normal pressure of 390 lb. and a total temperature of 700 deg. fahr. Steam is bled at the 3rd, 5th, 8th, and 10th stages at full load pressures of 193, 99, 30, and 9 lb. absolute respectively. The turbine is designed for highest efficiency at 25,000 kw. load; and when bleeding steam at four points the unit can produce a net station send-out of 36,000 kw., which is the company rating of the machine. A considerably larger output can be produced by bleeding at the two lower points only.

GENERATOR COOLING

Both the main and auxiliary generators have closed re-circulating air cooling systems with two banks of coolers in each, one bank using condensate and one harbor water. The harbor water coolers are connected in parallel with the condenser circulating water system but have a roof tank connection for emergency. Condensate cooling is sufficient except for the summer months. The harbor water bank alone will provide sufficient cooling for maximum requirements.

Oil coolers are provided in duplicate, one using condensate and one harbor water, and arranged for individual or series oil circulation.

CONDENSER

A 30,000-sq. ft., two-pass condenser is bolted directly to the bottom of the turbine exhaust casing and is supported partly by the casing and partly by springs on structural piers on the basement floor. The circulating water passages are so arranged that the cooler water leaving the air devaporizing and cooling section is returned in the second pass in the annular ring of tubes around the outside of the top section with which the exhaust steam first comes in contact. The shell is eccentric with the tube sheet, providing a steam belt which on one side extends to the hot well, which prevents excessive condensate depression.

The tubes are rolled into both tube sheets, a new feature of design that is discussed in other papers.

AIR REMOVAL

Air is removed from a devaporizing section at the

bottom of the condenser opposite the steam belt through two 10-in. openings which are joined in a 12-in. manifold leading to an 8-in. manifold on a three-element two-stage steam jet air pump located on the turbine platform. This pump is provided with a two-pass inter-condenser, containing 314 sq. ft. of surface and cooled by condensate only. Vent steam from the two top stage bleeder heaters and from the vent condenser of the deaerating heater is also condensed in the inter-condenser, the drips from which drain through a 12 ft. seal to the main condenser. The exhaust from the second stage jets is condensed in the after condenser. The combined capacity of the three elements on the pumps is 59 cu. ft. of free air per minute at 29 in. vacuum. Two elements at 17 cu. ft. per minute each are normally sufficient.

CIRCULATING WATER

Circulating water from the Patapsco River passes through bar iron trash racks at the water front, under a submerged arch and through traveling water screens into an intake tunnel which will extend the length of the turbine room. Space is provided for four screens which are located outside and arranged for removal by a floating derrick. Each condenser is supplied by two motor driven pumps of 20,000 gal. per min. capacity each, both of which are required under full-load conditions in the summer. The tail pipe discharges in a tunnel common to all units, which is carried westward under the coal field to the water front. A steam jet ejector is used for priming the circulating water pumps.

HOT WELL PUMPS

Condensate is removed from a 1000-gal. hot well by two motor-driven two-stage opposed impeller type hot well pumps, either of which is of sufficient capacity for full rated load operation.

BLEEDER HEATERS

The 3rd, 5th, and 10th stage bleeder heaters, the evaporator condenser, and the after condenser are of the vertical closed type with four passes each. The construction of these heaters is shown in Fig. 9. The tube surface is made up of ¾ in. outside diameter, No. 14 gage Admiralty tubing, which is bent into hair-pin loops with both ends rolled into a single tube sheet. The shells are of steel with hammer welded joints. Water boxes on the high pressure heaters for the first unit are of cast steel, but on the second unit will be of rolled plate. Steam is introduced in each case below the tubes and the baffles are arranged so that a vapor cooling chamber is provided to which the air vent connection is made at the side of the shell.

The 8th stage heater is of direct-contact deaerating type in which part of the bled steam is used in a section into which the condensate is sprayed through jets and part is used in another section similar to the open type feed heater in which trays are located and from which the air is removed. The pressure in the heater varies

as the bled steam pressure varies. This heater is in the boiler house at an elevation of 80 ft. above the boiler feed pumps, which take their water from it. With a shell capacity of 6400 gal. it serves as a closed surge tank. The only condensate in the cycle which comes in contact with air is the condensed drip in the after condenser, which passes through the deaerating heater on its way back to the boiler.

EVAPORATOR

Make-up is supplied by a low heat level interstage evaporator of the vertical single-effect recirculating film type using city water as feed at a maximum rate of 10,000 lb. per hour corresponding to approximately 2½ per cent of the total full-load turbine steam flow. Fifth stage steam is used and the vapor is condensed in the evaporator condenser. The capacity may be increased by a by-pass connection of the vapor line to the 8th stage heater. The evaporator is located adjacent to the closed type bleeder heaters, under the

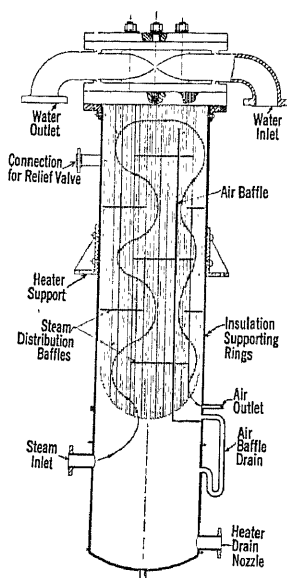


FIG. 9—BLEEDER HEATER OF HAIR-PIN LOOP CONSTRUCTION

turbine platform. Removable plates in this platform allow the handling of the shell and tube bundle of the evaporator as well as of the three heaters and two condensers with the turbine room crane.

PUMPS AND WATER STORAGE

One five-stage motor driven boiler feed pump of 1000 gal. per min. capacity is provided for each main unit with one spare unit of the same size for each group of two units so arranged as to be available for either. A steam turbine-driven four-stage pump serving as a boiler protector only is installed with its suction connected to evaporated water and city water storage only and its discharge connected to the boiler feed mains.

Harbor water for miscellaneous cooling purposes is elevated from the screen well by two 800 gal. per min. motor-driven pumps in duplicate. A 15,000-gal. roof

tank floats on the line. Two 1200 gal. per min. pumps furnish water from the same source at 125 lb. pressure for screen washing and ash sluicing. All of these pumps have bronze casings.

Condensate for make-up storage is removed from the cycle as it leaves the generator air coolers. A float in the 8th stage heater surge tank controls the amount removed. A tank of 21,000 gal. capacity at an elevation of 30 ft. above the turbine room floor receives this make-up, and further storage in two 15,000 gal. tanks is provided on the boiler house roof. Two 800 gal. pumps, arranged for either city water or evaporated water are used in this service.

City water is brought to the plant by lines from two sources. A float valve controls the supply to a 15,000-gal. tank on elevation 35, from which it is pumped to a 15,000-gal. tank on the roof.

PIPING

The single row of boilers parallel to the row of turbines makes for a very simple steam piping system. Steam is conveyed from single outlets on the Nos. 1 and 2 boilers to a four-neck manifold, from which is taken the No. 1 turbine lead and a tie to a second manifold. The second manifold is a duplicate of the first, with a connection from the No. 3 boiler and the No. 2 turbine in addition to a tie to a third future manifold. These manifolds are of seamless steel, forge welded, 25-in. outside diameter pipe. Boiler and turbine leads are 16 in. outside diameter seamless tubing designed for steam velocities of 9000 ft. per min. at rated load. Sargol joints, 600-lb. standard, with serrated faces are used throughout but valve flanges are made up with gaskets and not welded. An emergency closing valve was used on the No. 1 turbine lead but it will be omitted on the second unit. Motor-operated stop valves are used with additional remote control stations on the turbine platform.

One main and one auxiliary header is used on the boiler feed system with one feed line to each boiler from each header. All feed lines are of seamless steel extra heavy iron pipe size. Line joints and tee connections are all acetylene welded and fittings are employed only where welds cannot be used.

Lines conveying harbor water are of cast iron below the turbine room floor level, of extra heavy genuine wrought iron above the floor in sizes 2½ in. and larger and of standard pipe size brass in smaller sizes. Circulating water lines are of cast iron, atmospheric exhaust relief of fabricated steel plate welded inside and out at the joints, and all lines carrying condensate and city water are of standard steel. Welded joints have been used throughout wherever possible. The extensive use of welding has made it possible to group in a gallery space 11 ft. 6 in. wide by 11 ft. 4 in. high, with an unusual degree of accessibility, some 16 headers which will extend the length of the plant, only two of which are of sizes less than 6 in. diameter.

Eighty-five per cent magnesia insulation with a cement finish covered by 8-oz. Army duck is employed throughout. It is protected on high temperature lines by a layer of asbestos composition. Heater shells have a hard cement finish. Water boxes, turbine casing flange, and evaporator shell flange have removable blankets of asbestos fiber and cloth.

CABLE TUNNEL

The generating voltage is 13,700 at the bus and about 13,300 at city sub-stations, the nominal voltage at the point of usage being 13,200. From the power house the energy is carried through the cable tunnel, shown in Fig. 10, to the isolated phase switch house by means of three 1,000,000-cir. mil lead sheathed cables per phase.

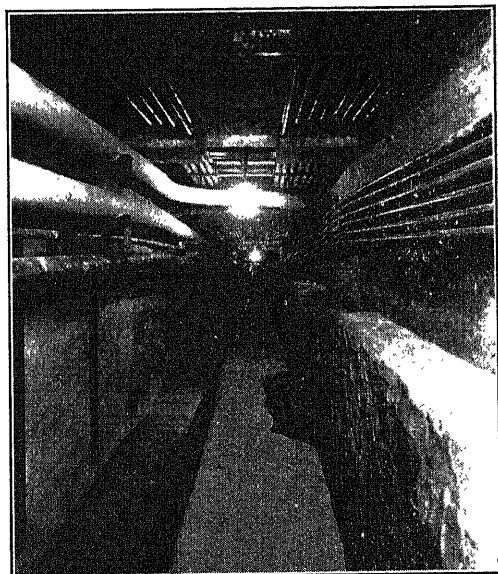


FIG. 10—VIEW OF CABLE TUNNEL LOOKING SOUTH

Insulation used on these cables is the standard for sub-station work—being 4/32-in. thick 30 per cent Hevea rubber and 10/32-in. Varnished Cambric. In order to prevent heating due to heavy currents in the lead sheaths, special phase arrangements were followed in pulling the cables into the ducts and the sheaths were grounded only in the centers, thus materially reducing the circulating currents.

SWITCH HOUSE

The switch house shown in section in Fig. 11 has a basement and six floors. The side aisles of the basement are used for the high-tension potheads, this being the first and only place the phases come together. The center of the basement has been reserved for a 4000-volt distribution substation in the future. The first main floor has *C* phase equipment, the second carries *B* phase, and the third *A* phase. The operating mechanisms for the oil switches, bus disconnects, and pothead disconnects are located on the fourth floor together with the connections to the specially calibrated instrument transformers used on the water rate test circuits.

The fifth and sixth floors will extend over only a portion of the ultimate building and are used to house the control conduit boxes, station emergency lighting storage battery, and the operating room.

CONTROL BOARD

The main control board in the operating room is a double board, semi-circular in shape. The center panels on the inner board carry the indicating meters

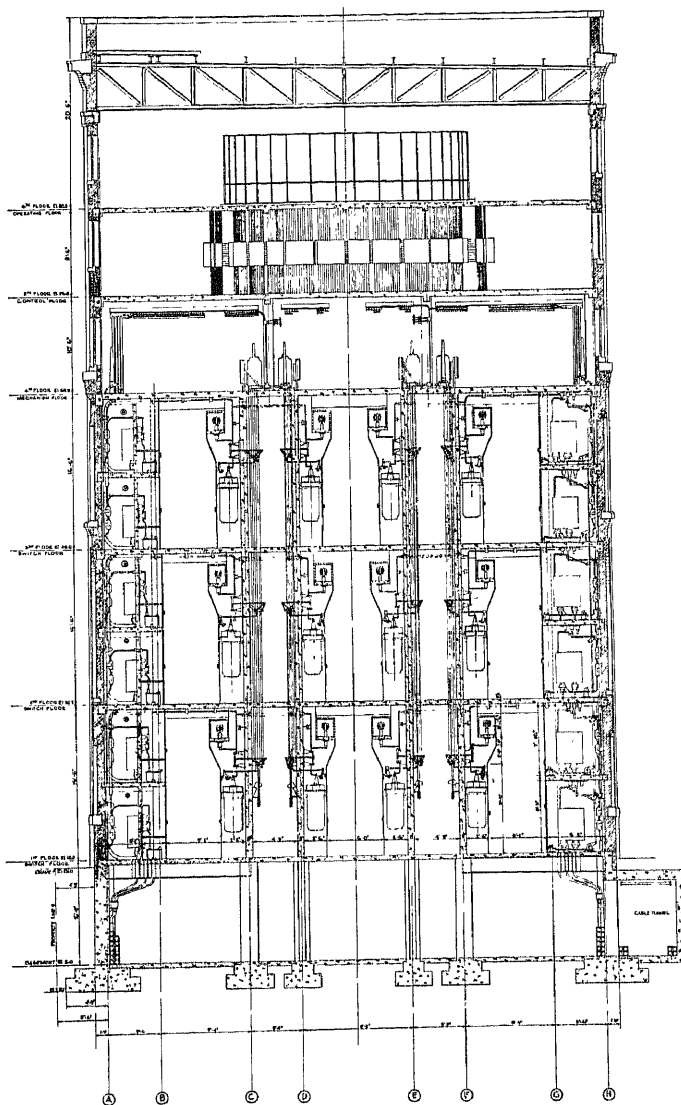


FIG. 11—CROSS-SECTION OF SWITCH HOUSE

and controls of the generators, while the end panels on either side control the outgoing feeders. The outside semi-circle carries the integrating watt-hour meters, relays, test switches, etc., for these various circuits.

There is another small board on the opposite side of the room which is used for the d-c. control circuits and the storage battery switching and charging.

OIL SWITCHES

The oil switches on the outer ring bus have a rupturing capacity of 40,000 amperes, r. m. s. at 15,000 volts, based on the standard A. I. E. E. duty cycle, and they

are built to operate on 15,000 volts, although standard 25,000 volt insulation is provided throughout. All generator and test bus tie circuits are equipped with 2000-ampere apparatus, while the outgoing feeders have 600-ampere oil switches and disconnects. Provision is made for the future installation of 4000 ampere bus sectionalizing switches.

The inner ring bus is equipped with switches having a rupturing capacity of 40,000 amperes on the generator and test bus tie circuits only. The feeder switches have a rated rupturing capacity of 30,000 amperes.

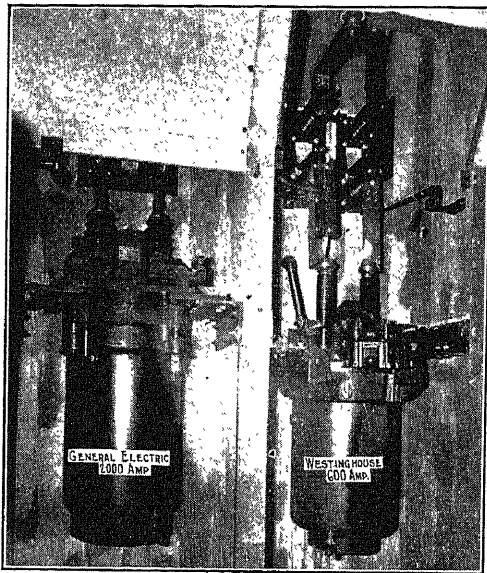


FIG. 12—2000-AMPERE GENERAL ELECTRIC (LEFT) GENERATOR SWITCH AND 600-AMPERE WESTINGHOUSE (RIGHT) FEEDER SWITCH

Fig. 12 shows a General Electric 2000 ampere generator switch on the left and a Westinghouse 600 ampere feeder switch on the right, both single pole for isolated phase mounting.

MAIN CONNECTIONS

The main connections of the switch house are seen in wiring diagram Fig. 13, which indicates two ring buses, giving a very flexible system.

REACTORS

Each three-phase feeder is equipped with three single-phase reactor coils, one on each phase floor, these coils having an impedance of $\frac{3}{4}$ ohm which limits a dead short circuit or ground to a maximum of 10,000 amperes, which is only one-third or in some cases one-fourth of the rated rupturing capacity of the switch. This same plan of limiting short circuits on feeders is employed in other generating stations and in substations and has resulted in greatly reducing interruptions and in maintaining bus voltage practically undisturbed by cable short circuits.

METERING AND RELAYS

On account of the strict isolated-phase system used it is necessary to connect all current and potential

transformer circuits YY, thus necessitating 176-volt potential coils in some of the instruments. All neutrals of the current and potential circuits as well as those of the main generators are solidly grounded, while those of the auxiliary generators are left ungrounded.

A multi-element integrating watt-hour meter actuating a printometer totalizes the plant generation and gives regular demand readings hourly.

The outgoing feeders go to the city substations in groups of three, each group having selective differential relay protection by means of current balance in addition to the usual overload features. The machine oil switches are relayed to open only in case of a breakdown in the machine itself or in the leads to the switch house, differential protection being obtained with current transformers added to the neutrals. Overload on the machine circuit causes the field breakers to open and reclose, thus temporarily dropping load without cutting the generator off the bus.

EXCITATION

Each machine has its own exciter bus which supplies excitation to the fields of both the main and auxiliary generators. Power is usually fed into this bus from the shaft exciter, but an emergency supply is available from a 200-kw. motor generator set.

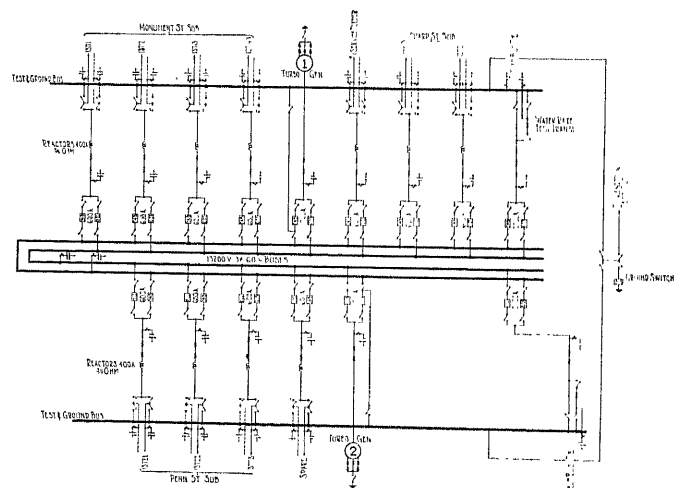


FIG. 13—ONE LINE WIRING DIAGRAM OF SWITCH HOUSE, NO. 1 AND 2 UNITS

250-VOLT CONTROL

Throughout the plant is used 250-volt d-c. control. This voltage was adopted to conform with present day design. It effects a material saving in copper, compared to 125 volts due to the large currents necessary to handle present day equipment, and the long runs between the various parts of the plant. It also allows the d-c. generators to be rated as spare exciters, when they are of sufficient capacity.

LIGHTING

Lighting in the main plant is a three-phase star system with grounded neutral. All circuits are run

three-wire 120-208 volts through the panel boards with the neutral solid. In this way the failure of a single-phase transformer would only extinguish one-half of the lights on each circuit. The emergency circuits are automatically transferred from two-phase, three-wire, to d-c. three-wire when the voltage falls to 85. Return from the emergency d-c. supply to the normal transformer feed must be made by push button on the transfer contactor panel.

460-VOLT AUXILIARIES

Station auxiliaries are designed for 460 volts rather than 2300, because the lower voltage motors were lower in cost and kept in manufacturers' stocks. It was felt that the lower voltage was also somewhat safer and could be handled well by carbon circuit breakers. Carbon circuit breakers occupy less space than oil switches that would be required for 2300 volts. Their cost was lower and they are subject to inspection during operation as they are mounted on the front of the auxiliary switch board. The fire hazard with oil switches is also avoided.

AUTOMATIC COMBUSTION CONTROL

The supply of fuel and air to the boilers and the removal of gas is controlled by Bailey automatic equipment which governs the speed of the forced-draft fans, induced-draft fans, and coal feeders. There is a separate control panel for each boiler. From this panel, the boiler operator controls auxiliary equipment and with the aid of signal lights and meters can tell at any time the operating condition as regards pressures, steam flow and electric power requirements for the various boiler auxiliaries. The electric circuits controlling the fans, feeders, etc., have been interlocked to shut down the equipment automatically in the event of failure of any part of the apparatus which might result in explosive mixtures in the furnace.

The induced and forced draft fan controls are the most unique in the plant. Due to the large size of the boilers and the high guaranteed rating of 550 per cent nominal rating, each of the boilers requires 1500 hp. for the four fans when operating at maximum rating. This is divided up as follows: two 200-hp. forced draft fans which introduce fresh air to the combustion chamber, and two 550-hp. induced draft fans which blow the hot gases up the stack.

The automatic combustion control used requires that the fans be able to follow very closely a predetermined speed curve of great range. To do this with a-c. motors a double speed primary is used, arranged for series connection for the first half of the range and for parallel connection the second half; large drums being used to regulate the secondary resistance for intermediate speeds.

The control for each fan consists of a low-speed secondary regulating resistance drum, a transfer switch for changing the number of poles by altering primary connections, a high-speed secondary regulating

resistance drum, a balanced high-speed drum for the last five-speed points, a torque switch for starting, and the necessary circuit breakers and relays for interlocking and automatic protection. This combination of apparatus provides approximately 55 speed points for each fan.

In order to start up the fans it is only necessary to push a start button on the boiler panel which closes a latched-in relay. This places the fans in an operative condition. When the automatic combustion control calls for more draft the drums begin to rotate, the primary circuit breakers are automatically closed, the torque switches revolve until the motor starts up, and the drums are set on the desired operating point automatically. In the case of the induced draft fans, stack dampers are controlled by the same combustion control drive and a range of natural draft is utilized before the primary breakers close and the fans start. The speed range of induced draft fans is from 110 to 870 rev. per min. and on the forced draft fans the speed range is from 145 to 1170 rev. per min.

Primary air fans are controlled by manually operated secondary regulating resistance drums having 11 points, five of which are balanced. Their speed range is from 700 to 1750 rev. per min.

An elaborate system of interlocks has been provided to take care of emergencies in operating and to prevent situations which might cause an explosion of the powdered coal mixture in the boilers. Relay protection is provided to trip the fan circuit breakers on loss of 460 volts service. In case the two induced draft fans are tripped the two forced draft fans are automatically removed from the line to prevent the formation of positive pressure in the furnaces. If, at this time, the combustion control is still calling for mechanical draft, three of the four coal feeder motors are shut down. However, it is possible to operate the boilers at low ratings on natural draft and provision is made to prevent the shutting down of the coal feeders when operation is being carried on at low ratings. If the primary air pressure should fail three of the four coal-feeder motors are shut down and the steam aspirators are turned on. If positive pressure should occur in the furnace the forced draft fans and three of the coal-feeder motors are automatically shut down. Latched-in relays are used at the head of the various interlocking trains in order to prevent the shutting down of the fans in case of a failure of the d-c. relay supply circuits. The loss of control voltage will only prevent a change in speed of the fan motors, and will not cause them to shut down.

The coal feeder motors having an extreme speed range by means of automatic field control are direct current. Their bus is normally supplied by a 50-kw. motor-generator set with an emergency transfer breaker to operate in case of low voltage, throwing the load on to the main d-c. bus. The speed of these coal feeder motors is controlled by an automatic combustion con-

trol drive, which operates a gang of four field rheostats for each boiler. The motors are started and stopped by means of push buttons on the main boiler panels which control single step armature resistance starters. Interlocks have been provided as mentioned before to cut off three of the four motors in each group in case of trouble. These coal feeder motors are 5-hp., 250-volt, d-c., enclosed, and have a speed range of from 400 to 1600 rev. per min.

BOILER FEED CONTROL

The 500-hp. boiler feed pumps are controlled by motor operated drums having 36 points and a speed range of from 1400 to 1750 rev. per min. The speed

also have hand operated drums with a speed range of from 175 to 350 rev. per min. in eleven steps, five of which are balanced.

CARBON CIRCUIT BREAKERS

Recent tests made by this company demonstrated that for low voltage, high current work, carbon circuit breakers and contactors performed satisfactorily in clearing the short circuits that might be imposed upon them at Gould St. From our point of view this was highly satisfactory, because such breakers and contactors are particularly well suited for inspection and maintenance. Being on open panel boards, heating or other troubles are readily discernible and contacts are easily inspected. Carbon circuit breakers are used

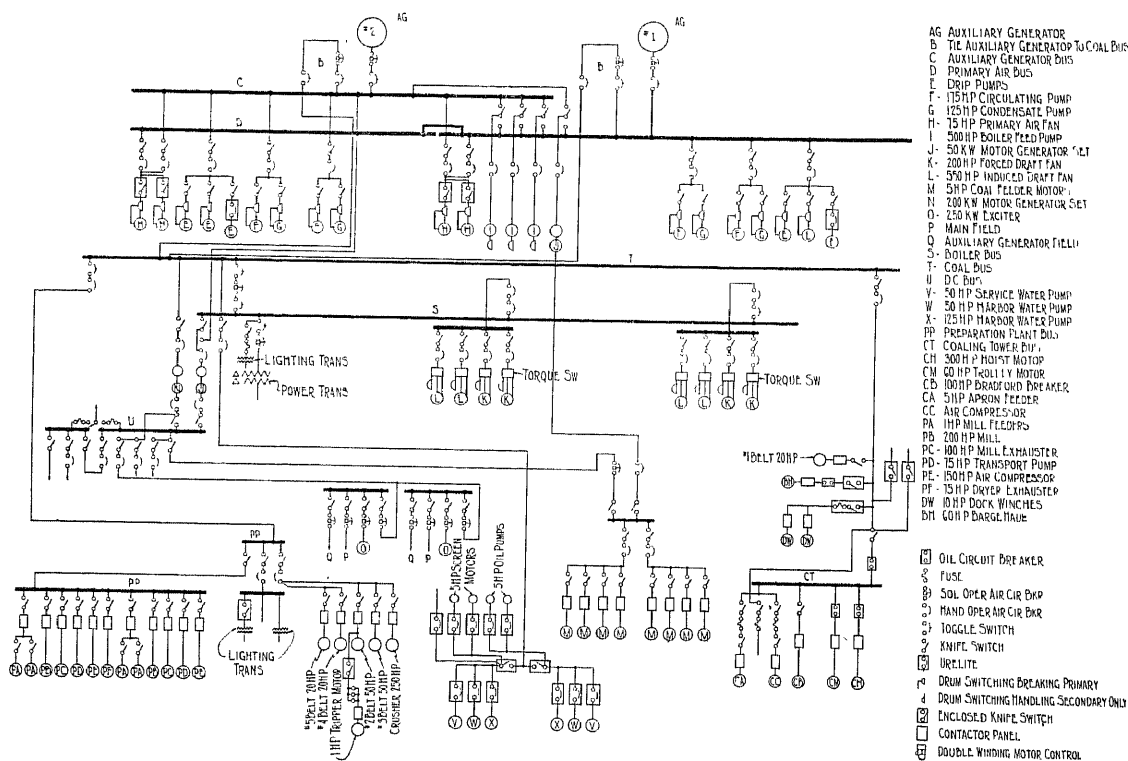


FIG. 14—ONE LINE WIRING DIAGRAM OF A-C. AND D-C. AUXILIARY SERVICE FOR NO. 1 AND 2 UNITS

controls are arranged either for push button or automatic operation.

The automatic operation of each pump is controlled by the differential pressure between the pump discharge and the boiler drum. This differential, which is limited to a certain minimum, is varied approximately as the square of the load by a diaphragm on the regulator which is connected to the discharge duct of the forced draft fans. The process is selective by means of check valves in the case of the fan pressure and boiler pressure, so that the control is by the fan or boiler of highest pressure.

The 125-hp. condensate pumps have 24-point hand operated secondary regulating resistance drums with eight balanced points, giving a speed range of from 1400 to 1750 rev. per min. The 175-hp. circulators

exclusively on "essential" circuits—where interruptions must be reduced to an absolute minimum. Here it is necessary that a "latched-in" mechanism be used instead of depending on a holding coil, which is subject to failure. For the auxiliary generator, station service transformer, and other main feeders a type of circuit breaker was chosen with a mechanical trip-free arrangement, such that when closed in on a short circuit by remote control (solenoid operation) it would trip out the instant the short circuit was established. This feature of being trip-free throughout the entire stroke had to be developed especially for this job on the large 5000-ampere, three-pole breakers used on the station service transformers, and fan bus ties, although the smaller remote control and hand operated breakers were already available, so equipped.

460-VOLT WIRING

Fig. 14 gives the wiring diagram for 460-volt auxiliaries. Separate operating buses are provided for the essential auxiliaries of each turbine and are supplied by the auxiliary generator. These buses are arranged in pairs with the ends overlapping so that the boiler feed pumps, primary air fans and coal feeder motor-generator set for each two units may, by means of double-throw knife switches, be operated from either bus. In addition each bus carries the circulator pumps, condensate pumps, and drip pumps of its own machine. It will be noted that the circulator and condensate pump feeds are arranged in pairs of one each. This necessitates the shutting down of only one motor of each class in case of a breaker tripping.



FIG. 15—VIEW OF STATION AUXILIARY SERVICE SWITCHBOARD

The essential auxiliaries are equipped with overload devices which function only on short circuits. In other words the circuit breaker trips or the CO relays are set to take the motor off the line only when the current exceeds the pull out torque value. Fig. 15 shows the 460-volt switchboard.

STATION TRANSFORMERS

The station service transformers at present consist of three 1000-kv-a., 40-deg. cent. rise, 1250-kv-a., 55 deg. rise, or 1500-kv-a., one hr. overload rating single-phase oil-insulated self-cooled 13,200/460-volt transformers, connected delta delta. Relays are arranged so that an overload on this bank would trip off the coaling tower, the coaling bridge, and the preparation plant. The bank also has differential protection which trips the high tension oil switch as well as the low tension breaker, in case of internal trouble.

COMMUNICATION

Communication throughout the plant is effected by a telautograph system having six stations, code calling by means of air whistles being used. There is also an intercommunicating telephone system which reaches strategic points in the entire plant as well as a number of

Bell stations connected to the company's private branch switchboard for outside calls.

INVESTMENT COSTS PER KW. CAPACITY

Throughout the design of the Gould St. Plant the object was to secure maximum reliability with minimum total costs per kw-hr. By total costs is meant not only operating labor and superintendence, maintenance, and fuel cost, but fixed charges on the investment. This criterion was used in the choice of apparatus, the cost of the apparatus being weighed against its ability to reduce production costs.

We give below a table of the actual cost of the first unit, and the estimated costs of three additional units; the estimated cost of the completed plant of 144,000 kw. being \$88.26 per kw.

	1 unit (Actual)	2 units (Est.)	3 units (Est.)	4 units (Est.)
1. Investment cost as per Report of June 20, 1927 . .	\$4,681,821	\$7,396,224	\$10,090,322	\$12,709,909
2. Capacity—kw . . .	36,000	72,000	108,000	144,000
3. Cost per kw	\$130.05	\$102.73	\$93.43	\$88.26

The wide spread between the cost per kw. of the first unit and the cost per kw. of the completed plant is due to the many items included under the first unit, which are designed for the completed plant, such as, land, relieving platform for coal storage, coal handling, preparation plant, etc.

The capacities given in the above table are the net send-out capacity with four-stage bleeding.

Under two-stage bleeding conditions capacity is increased considerably and a net send-out capacity of 40,000 kw. is readily obtained and will be obtained in the event of need, for peak load conditions. Figuring this higher capacity the investment costs become as follows:

	1 unit (Actual)	2 units (Est.)	3 units (Est.)	4 units (Est.)
1. Investment cost as per Report of June 20, 1927 . .	\$4,681,821	\$7,396,224	\$10,090,322	\$12,709,909
2. Capacity—kw . . .	40,000	80,000	120,000	160,000
3. Cost per kw	\$117.05	\$92.45	\$84.08	\$79.44

The investment figures given include all expenses of every nature in connection with this plant, covering such items as preliminary engineering, old buildings used, interest during construction and during tuning up period, also a portion of the floating equipment of the company properly allocated to serve this plant.

ACKNOWLEDGMENTS

Another paper is submitted at this meeting covering studies on design prepared by Messrs. Leilich, Follmer, Dannettel, and Fallon, to whom credit is given for the information in this general paper.

Mr. Penniman of the Company's staff is also presenting a paper on the operation of Gould St.

Discussion

For discussion of this paper see page 878.

Design Studies for Gould Street Generating Station

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Synopsis.—Developments in the central station art have been so rapid within the last few years that many of the recent outstanding stations differ considerably in major elements of design.

In the following, are briefly outlined, high points of the analyses upon which the principal features of the Gould Street design were based.

THIS paper covers briefly the various studies and investigations upon which the Gould Street design was based. Load studies clearly showed the need of additional 62½ cycle generating capacity in 1927. As a result, a single unit station of approximately 35,000 kw. was authorized. The major features to be settled before equipment specifications could be prepared and detail design work started were: steam pressure and temperature; number and size of steam generators; type of firing—stokers or pulverized fuel; heat cycle or working heat balance; the most economic design of condenser; auxiliary drive—electric or steam.

STEAM PRESSURE AND TEMPERATURE

The general trend of pressure and temperature was upward, as shown by Fig. 1, which was plotted from

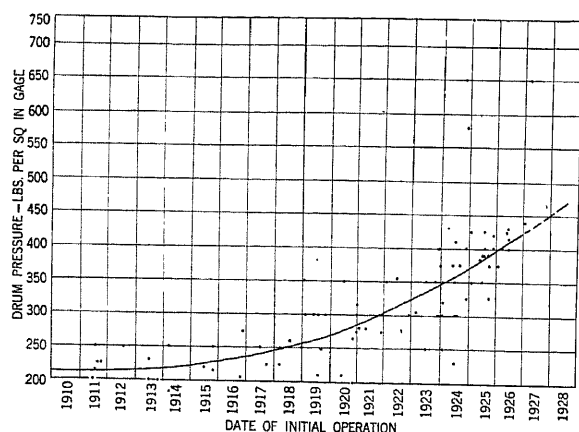


FIG. 1—TREND OF BOILER DRUM PRESSURE IN POWER PLANTS

the specifications of 85 stations. Operating records of other plants were studied and most of the new stations visited, at which time design and operating problems were discussed with the engineers. Essentially the problem was to select a pressure and a temperature that would result in maximum reliability and minimum total costs.

Operating experiences with pressures up to 400 lb. and total steam temperatures up to 725 deg. fahr. were sufficiently extensive to show clearly that from the

¹ With Consolidated Gas, Electric Light & Power Co., Baltimore, Md.

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standpoint of reliability and operating difficulties these limits could be adopted for a conservative design. To obtain concrete figures showing the effect of pressure on costs and economy, detailed estimates based on a 40 per cent capacity factor, of a 250 lb.—700 deg. fahr., and a 400 lb.—700 deg. fahr. station were made. It is interesting to note that the estimated cost per kw. of the 250-lb. station was 4 per cent greater than for the higher pressure, and the over-all economy of the 400 lb. installation was six and one-half per cent better. Studies of relative costs of 600 and 700 deg. fahr. equipment showed that the improved economy of the higher temperature would justify the slightly increased cost of superheaters and added thickness of high temperature insulation.

A maximum drum pressure of 450 lb., with 725 deg. fahr. temperature at the superheater outlet was selected. This corresponds to 390 lb., 700 deg. fahr., at the turbine throttle. This temperature and pressure were selected after numerous conferences with the engineers of the various manufacturers and at the same time the possibilities of extension, using 1200 to 1500 lb. at the throttle of high-pressure turbines, exhausting at approximately 400 lb., into existing mains, were not overlooked.

NUMBER AND SIZE OF STEAM GENERATORS

The boiler specifications called for working pressure in the drum of 425 lb. gage and total heating surface of 26,500 sq. ft. The bidders' guarantees covered operation up to 500 per cent rating, with 15 per cent $C O_2$, as it had practically been decided to use water-wall furnaces. The contract as awarded specified operation up to 520,000 lb. of steam per hr., which corresponds to approximately 550 per cent of rating, based on the total boiler and furnace heating surface. The trend of fixed and operating cost records of representative stations showed fixed costs as an increasing percentage of total costs and it was obvious that operating and kilowatt investment costs would be reduced if a small number of large steam generating units designed to operate efficiently over wide ranges of rating could be used. The experience up to that time indicated that water-cooled walls made it possible to operate at high ratings and over a wide range.

Load and operating conditions indicated that the

turbo-generator units should have capacities of from 30,000 to 40,000 kw. each. Numerous plant layouts were made, and based on these the ultimate capacity of the station was tentatively set at four units, or approximately 140,000 kw. Estimates of investment costs for both equipment and structure showed distinctly lower costs for a design based on one boiler per turbine. The boiler and furnace designers were ready to build and guarantee performance on equipment on this basis. With the cross-drum type of boiler, which was preferred by the engineers, additional heating surface could be economically obtained by increasing the length of the tubes and making the tube bank the maximum width consistent with drums having no girth seams.

TYPE OF FIRING

Many of the newer plants were using pulverized fuel, but it was not obvious that the advantages of this type of firing were such that it should be adopted without careful study. Operating engineers of plants using the two types of firing were consulted and the merits of each carefully weighed. Proposals on stokers and pulverized

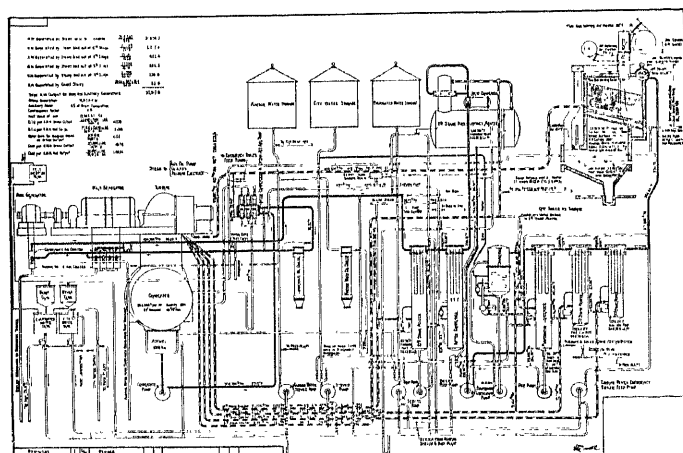


FIG. 2—FLOW SHEET REPRESENTING FULL-LOAD OPERATION WITH FOUR-STAGE BLEEDING AND 29 IN. VACUUM AT TURBINE EXHAUST

fuel were obtained and economic set-ups, covering both fixed and operating costs, prepared. Although pulverized fuel investment costs were higher, when the merits of the two systems—tangible and intangible—were carefully considered it was finally decided to adopt the central system of pulverized fuel firing.

HEAT CYCLE

A primary consideration was the selection of a heat cycle that would result in the lowest total cost, when both fixed and operating charges are included. Numerous set-ups were prepared, and economies calculated. Each showed that four-stage bleeding and air preheating would yield a greater return on investment than two or three bleeding stages combined with an economizer and preheater. The four-stage bleeding cycle has a further advantage of an approximate increase of 10 per cent capacity at only a slight drop in economy when operating under peak or emergency conditions with the two top-stage bleeders shut-off. In addition, for the machine under consideration a normal increase in capacity of approximately 300 kw. was possible, this being based on the power generated by the steam up to the first bleeding point, which steam by reason of limiting conditions of area in the lower stages could not have been used economically in the machine when designed for three-stage bleeding only. The foregoing advantages, and an economy increase of approximately 0.45 per cent by the use of four stages as compared to three, led to the adoption of the four-stage bleeder cycle.

Fig. 2 is a flow sheet showing the station heat balance for full load generation operating under 29 in. of vacuum.

The normal course of the condensate leaving the hotwell pumps is in order through the steam jet air pump inter-condenser, oil cooler, generator air cooler, tenth stage heater, after-condenser, eighth stage deaerating heater, boiler feed pump, evaporator condenser, fifth stage heater, and third stage heater to the boiler feed mains at a final temperature of 365 deg. fahr. Bypasses are provided individually for the oil cooler and the generator air cooler bank. Bypasses are also provided for the tenth stage heater and after-condenser as a group, and for the evaporator condenser and top-stage heaters as a group. Drips are cascaded from the top stage heaters to the evaporator condenser from which they are pumped into the condensate line leading to the eighth stage heater. Drips are cascaded also from the after-condenser to the tenth stage heater from which they are pumped into the condensate line leaving the tenth stage heater. The drip pumps are of the same type as the hotwell pumps, driven by slip-ring motors. Calculated feed water heater performances are given in Table I.

TABLE I
CHARACTERISTICS OF FEED WATER HEATERS

Equipment	Lb. of water heated per hr.	Temperature deg. fahr.		Water press. loss in ft. of water	Heating surface —sq. ft.	Terminal difference in deg. fahr.	Heat transfer in B. t. u. per sq. ft. per hr. per deg. fahr. mean temp. difference
		In	Out				
Third stage heater	414,000	316	365	14	1,420	10	520
Fifth stage heater	414,000	279	316	15	1,565	7.5	515
Evaporator condenser	414,000	252	279	14	1,550	5	510
Eighth stage heater	340,000	204	247	..	..	0	..
After-condenser	340,000	183	209	11	1,625	3	480
Tenth stage heater	310,000	92.5	182	11	2,000	5	455

Table II shows the calculated over-all B. t. u. per kw. hr. net station send-out. This is based on one boiler per turbine, auxiliary power 6 per cent of gross generation, over-all contingency factor 4 per cent, and throttle conditions 405 lb. absolute, 700 deg. fahr.

A turbine designed for non-bleeding operation was modified for bleeding conditions. Both the primary and secondary control valves admit steam to separate groups of nozzles which discharge through the buckets of the first wheel. This offered an advantage for bleeding at the third stage over designs where the secondary valve bypasses the first few stages. By increasing the steam flow areas in the first stages it was possible to admit sufficient steam for bleeding and still use the last stages as effectively in normal operation as for non-bleeding design. The non-bleeding machine was designed for 29 in. vacuum, but with the lower average vacuum of less than 29 in. expected at this particular installation, a greater quantity of steam is passed through to the condenser without increasing the leaving losses from the last stage and by reason of the power generated by this increased flow together with that generated by the additional steam admitted for withdrawal at the bleed points, the capacity of the turbine is considerably increased. A change from eleventh stage bleed-point to tenth stage gave an increase of 0.25 per cent in station economy.

TABLE II
B. T. U. PER KW. HR.—NET STATION SEND-OUT

Load	28 in. vac.	28.5 in. vac.	29 in. vac.
35,000 kw.	15,562	15,291	15,138
25,000 kw.	15,103	14,707	14,356
15,000 kw.	16,855	16,313	15,695

CONDENSER

The average injection water temperatures throughout the year and the heat rejected to the condenser under various loads and exhaust conditions were the bases for the selection of the economic amount of condenser surface. Fig. 3 shows the relation between the exhaust steam temperature and the kilowatt increase in turbine output per degree of decrease in exhaust steam temperature. This method of analyzing turbine performance is described in the N. E. L. A. Prime Movers Committee Report on Turbines, December, 1926. The curve, (Fig. 4), shows the relation between injection water and exhaust steam temperatures for different load conditions and different areas of condensing surface. From the load duration estimate, injection water temperatures, and Figs. 3 and 4, the relative fuel economies of the different size condensers were determined. For these calculations, fuel cost was taken as 0.224 cent per kw. hr. In the final comparison, fixed charges were estimated at 16 per cent except on tubes, against which 30 per cent was charged, corresponding to about a 5-year life. It was found that 30,000 sq. ft. was about the maximum justifiable surface. This corresponds to 0.833 sq. ft. per kw. of generator capacity.

It was essential that special effort be made to improve the purity of the condensate over that which ordinarily obtains in tide water plants; otherwise there would be no advantage in distilling the make-up, and the continuous operation of the boilers at high ratings would be seriously hampered. The point of attack was the

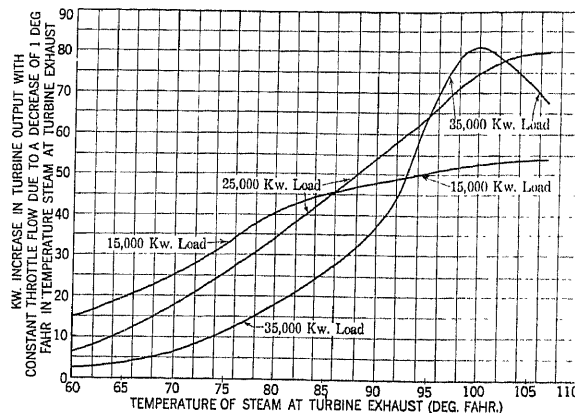


FIG. 3—GAIN IN TURBINE ECONOMY INCIDENT TO DECREASE OF DEG. FAHR. IN EXHAUST STEAM TEMPERATURE AT VARIOUS LOADS

leakage at the packed joints of the tubes. Floating tube sheets with rubber diaphragms as proposed by the manufacturers were not looked on with favor. Fixed tube sheets with tubes rolled in at both ends had been used in some instances in the Navy and it appeared

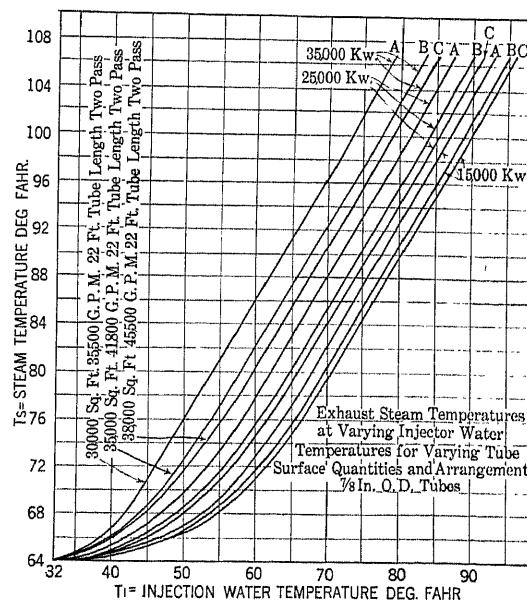


FIG. 4

feasible to adapt the principle to power plant service. It was found in tests made with an 18 ft. tube, set-up with the slight upward bow of $1\frac{1}{2}$ in. at the center of its length between fixed plates, that repeated reversals of hot and cold water through it sufficient to give it the expansion between plates that would be encountered in service, produced no change in the structure of the metal of the tube, as seen under the microscope, and

that the joints in the tube sheets remained tight. The tube was restrained in its vertical motion by the tube support plates, the holes in which were reamed to a special shape so that as the tube bends in expanding it has as much surface contact on the plate as possible. The shape of the expanded tube resembled a sine curve of about one and one-half cycles. The axial thrust of the tube against the sheets was as high as 425 lb. maximum, and at first it appeared that the staying of the sheets would be a difficult problem. On further

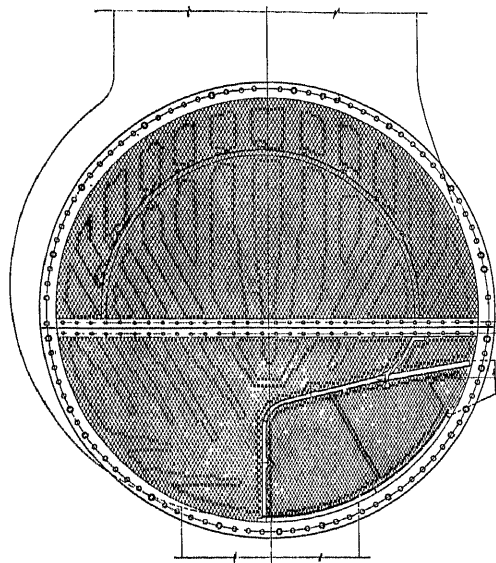


FIG. 5—INLET END TUBE SHEET LAYOUT FOR 30,000 SQ. FT. CONDENSER. (NOTE QUESTION MARK Baffle FOR GUIDING WATER FROM AIR COOLER TUBE SURFACE TO OUTSIDE RING OF TUBES IN SECOND PASS)

analysis, however, the logic of eliminating all stay bolts presented itself, and the tube sheet layout shown in Fig. 5, in which all stay bolts are omitted and tubes rolled at both ends into fixed sheets, was adopted.

The manufacturer agreed to construct a condenser in accordance with this design with the provision, however, that the purchaser assume all responsibility for its success or failure.

AUXILIARY DRIVE

Electric drive was selected for the auxiliaries. Some of the factors influencing this decision were:

1. Elimination of small high pressure steam lines and exhaust lines.
2. Easier control of the heat cycle, as the steam requirements of turbine driven auxiliaries are not necessarily a direct function of the generator output.
3. Relatively high economy of shaft driven generators as compared to individual turbine drive. The steam per kw-hr. requirement for the auxiliary generator is the same as that of the main unit.
4. Flexibility and reliability of electric motors and their control.

The general tendency in auxiliary drive is shown in Table III, in which 2300, 440, and 220 volts were the

prevailing a-c. potentials and 250 the prevailing direct current. Alternating current had been used in the greater number of installations and has the following advantages:

TABLE III
THE MAIN AUXILIARY CHARACTERISTICS OF CENTRAL GENERATING STATIONS

Year of initial operation	Auxiliary voltage			Boiler feed pump drive			Circulating pump drive		
	High 3000-2200	Medium 660-440	Low 250-110	Turbine	Turbine and motor	Motor	Turbine	Turbine and motor	Motor
Other years	0	1	2	2	1	0	3	0	0
1911	2	2	0	2	2	0	1	2	1
1912	0	1	0	1	0	0	0	1	0
1913	0	3	0	0	3	0	1	2	0
1914	0	1	0	0	1	0	0	0	1
1915	0	2	2	2	2	0	1	2	1
1916	1	1	0	1	1	0	1	1	0
1917	0	2	0	1	1	0	0	1	1
1918	1	3	0	2	2	0	0	2	2
1919	2	5	0	4	2	0	1	3	2
1920	3	0	1	3	3	0	2	2	2
1921	2	3	0	3	2	0	0	3	2
1922	2	0	1	0	3	0	0	1	2
1923	6	3	0	4	5	0	0	3	6
1924	12	3	0	6	8	2	0	2	12
1925	8	5	0	0	11	2	0	2	11
1926	6	0	0	1	4	1	1	1	4
1927	1	1	0	0	2	0	0	0	2

NOTE:

1. Since practically every station has electrically driven auxiliaries and all use alternating current except for a very small portion of the auxiliaries, such as stokers, it was assumed that all auxiliaries are driven using alternating current.

2. In cases where more than one voltage is used for the auxiliaries it was assumed that the larger auxiliaries, using the major portion of the auxiliary power, used the higher voltage.

3. The fans were, almost without exception, driven by motors.

4. Boiler feed pumps listed under turbine and motor drive are usually motor-driven with turbine-driven stand-bys.

5. The numbers under each heading indicate the number of stations in that class for the stated year of initial operation.

1. Available up to a capacity far in excess of auxiliary requirements, if transformers are used.

2. Relatively low costs of motors and control for applications with small ranges of speed control.

3. Absence of commutators (excepting brush shifting motors) and elimination of sparking, which is highly desirable in a pulverized fuel installation.

The selection of the most economical secondary voltage required extensive calculations and estimates in which were considered motor, control equipment, and installation costs, for voltages of 2300 and 440 and speeds from 575 to 1750 rev. per min., also space requirements and such intangibles as reliability, ease of inspection, etc.

A voltage of 2300 showed a saving in copper for long runs, but was considered undesirable because of the impracticability of inspection of the control equipment under load. The higher voltage motors are standard only in the larger sizes, and their use necessitates a low voltage supply for the motors below about 50 hp.

Fig. 6 is a curve of standard 60 cycle, 900 rev. per min. motor costs as of 1926. For squirrel-cage motors, it is

interesting to note that the cost curves for the two voltages, plotted with motor costs as ordinates and horse power rating as abscissas crossed at 138 hp. For wound rotor motors having the same synchronous speed as the squirrel-cage motors, the curves for 75 to 150 hp. showed the 2300-volt motor to be more costly over the entire range. From the standpoint of the motor cost alone the 2300-volt equipment is economically advantageous only for the larger size motors. For the range of sizes to be used in this station the 440-volt equipment was less expensive in practically every case.

Estimates of the cost of distribution cable showed that the cost per ft. is about equal at 100 hp.; below this

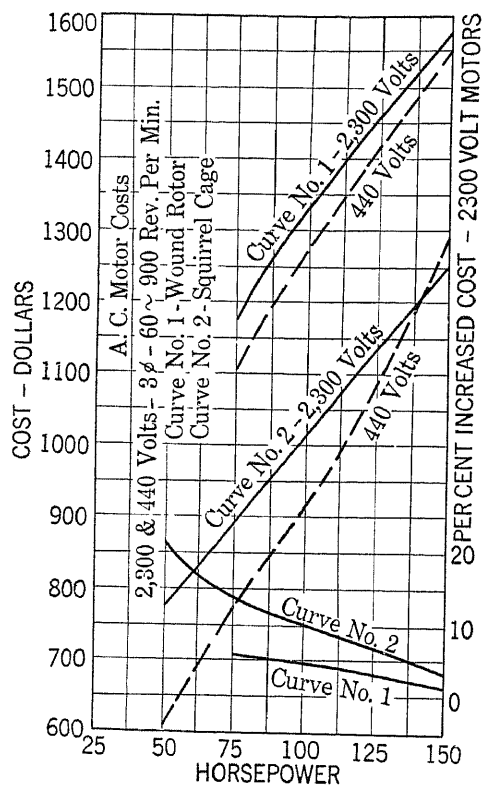


FIG. 6—CURVES SHOWING VARIATION IN COST OF VARIOUS SIZE WOUND ROTOR AND SQUIRREL CAGE MOTORS FOR 2300- AND 440-VOLT SERVICE

the cost advantage was in favor of the 440 to 460 volts. Cable costs were based on 440-volt lead covered cable with 600 volt insulation, and 2300-volt lead covered cable with 4000 volt insulation. When motor, control, and cable costs were added to the value of the space requirements, the 2300-volt system proved to be more expensive than the 440 volt. The final selection was 460 volts, 3-phase, 62½ cycles.

For the auxiliary circuits it was desirable that oil breakers be eliminated and contactors or carbon breakers used. It was obvious that the circuit interrupting devices should be of sufficient capacity to handle short circuits, and in order to arrive at a basis upon which to prepare specifications a number of tests was carried

out. The problem was put up to the manufacturers to furnish standard size contactors and circuit breakers rated up to 2000 amperes, which under test would handle repeated short circuits of not less than 20,000 amperes at 440 volts, 25 cycles, as the tests were to be made on 25 cycles. The contactors tested would not handle these currents, as after one or two operations the contacts had a tendency to "freeze." As a result of these tests, several of the manufacturers made modifications to their equipment, after which the contactors stood as many as five shots with practically no damage. In fact, one of the contactors interrupted about seven shots of 25,000 amperes with only a trace of pitting. With slight modifications, several of the standard carbon breakers handled about 20,000 amperes quite successfully. One feature insisted upon was that the breakers be non-closeable on short circuit, or trip free. Although the contactors handled the short circuits as well as the breakers, it was decided that the breakers were preferable to the contactors, for the reason that in case of failure of the holding coils, trip operated circuit breakers would not drop out, whereas contactors would.

Aside from the space requirements of the oil circuit breaker, there was the maintenance problem. There is no way of telling whether a breaker has been properly serviced or whether it needs attention, without removing the tanks, whereas with air break, pitting or burning of the contacts is readily discernible by inspection which can easily be made without dismantling the equipment. With a knowledge of the probable ultimate capacity of the station and the approximate maximum lengths of run and horse power of the auxiliaries, carbon circuit breakers were used on the auxiliary circuits with selected control equipment for handling the individual motor circuits. A control voltage of 250 volts, d-c., was used to eliminate the effects of a-c. disturbances on control apparatus and to insure quiet and more reliable operation of the contactors.

Auxiliaries were divided into two classes—essential, or those necessary for the uninterrupted operation of the turbine and boilers, and non-essential, or those such as pulverizing machinery—coal-handling plant and other equipment, a temporary shut-down of which would not interfere with the operation of the main unit and boilers. The essential auxiliaries are supplied with energy from the shaft driven alternator, the non-essentials from a bank of three 1000 kv-a., O. I. S. C. transformers. The arrangement is such that in the event of failure of the shaft driven alternator, the load is automatically transferred to the transformer bank. All auxiliaries are 460 volts, 3-phase, 62½ cycle, except the turbine room crane and the pulverized fuel feeder motors. These are supplied from motor generator sets, one running from the essential auxiliary bus, the other arranged to transfer automatically the load onto the transformer bank bus in the event of failure of the first motor generator set.

To reduce the voltage drop in the 460-volt bus, the copper in each phase was run in interleaved sections.

COMBUSTION CONTROL

Based on the performance of stations operating with automatic combustion control, it appeared that monthly operating efficiencies that approached quite closely to test efficiency were possible. Proposals on automatic combustion control were analyzed, and calculations based on the guarantees and a study of performance in existing plants indicated that the increase in monthly efficiency would justify the cost.

On account of the wide range of speeds—8 to 1 on both forced and induced draft fans—double winding, 6-phase, secondary slip-ring motors were specified.

A large number of speed points was necessary, and special control equipment consisting of drums and a motor-operated transfer switch for changing from the high to the low speed connection on the motor were installed. An excessive number of contactors would have been required to give the number of speed points specified. Also the cost of the control equipment using drums operated by the combustion control drive with provisions for manual operation and mechanical interlock between the drums was appreciably less than that of the contactor set-up.

Discussion

For discussion of this paper see page 878.

Operating Experiences at Gould Street Station

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Synopsis.—This paper deals with experiences in connection with the starting up and the initial operation of a steam-electric generating station, located at Baltimore, consisting of large cross-drum, sectional header, water tube boilers filled with water cooled furnaces which are fired by pulverized coal. The plant operates at 450-lb. pressure with 725 deg. temperature steam, the turbines being fitted for four-

stage bleeding. All auxiliaries are motor driven, the power being supplied either from direct-connected auxiliary generators, or from the main station bus bars through step-down transformers. This paper attempts to describe the major difficulties that were encountered in placing the plant in operation and outline the methods used in their elimination.

THE first cost of a power plant in any given location under the physical conditions existing at the site chosen, is largely a question of the fullest use of materials and equipment. This makes it desirable to use the smallest number of units of equipment of the largest permissible size, operated at the maximum allowable ratings. The auxiliary equipment must be carefully selected, with a view to maximum reliability, so as to permit of the installation of a minimum amount of spare apparatus. The installation of the equipment thus chosen, in order to use a minimum amount of space consistent with ease of access for operation and adequate maintenance, will result in the most economical balance between first cost and operating labor and maintenance costs. The actual manner in which this scheme has been carried out in the Gould Street Station of the Consolidated Gas, Electric Light & Power Company is described in two other papers.³ It is the purpose of this paper to present some of the actual difficulties encountered during the initial period of operation.

OPERATING PERSONNEL

The Gould Street plant represents our first experience in the burning of pulverized coal. For this reason, we were somewhat handicapped in the selection of an operating crew; especially so, since we considered it highly desirable to have as operators men who had been under observation for a sufficient length of time to satisfy us with regard to their fitness. Several months previous to the time that the first section of the Gould Street plant was scheduled to be ready for operation, certain men who were judged to be able to adapt themselves easily to the operation of pulverized coal equipment were selected from the operating organization. Also certain other men were employed and given some operating training at our Westport stoker-fired plant.

1. Supt. of Steam Stations, Consolidated Gas Electric Light & Power Co. of Baltimore.

2. Test Engineer, Consolidated Gas Electric Light & Power Co. of Baltimore.

3. The Gould Street Generating Station, by A. S. Loizeaux, page 853. Design Studies for Gould Street Generating Station, by F. T. Leilich, C. L. Follmer, and R. C. Dannett, page 866.

Presented at the Regional Meeting of District No. 1, of the A. I. E. E., Baltimore, Md. April 17-19, 1928.

COAL HANDLING EQUIPMENT

That equipment which we have classed as coal handling equipment consists of the coal hoist, Bradford breaker, barge haul and five conveyer belts, the second belt being provided with an airplane tripper for unloading to the coal storage yard, also with a hopper to receive coal reclaimed from storage. The pulverized coal transport equipment is considered separately.

Troubles which have developed in the coal handling equipment have not resulted in any great amount of inconvenience. Of major importance was the failure of some parts used in propelling the airplane tripper and its unloader belt, the drive being from the main conveyer belt by means of gearing and clutches. One of these failures resulted in a runaway condition with considerable damage narrowly averted. The weakness was inherent in the design and was obviated by changing the drive over to a cable haulage arrangement actuated by a separately controlled motor.

COAL PREPARATION EQUIPMENT

While a hammer mill, which is herein designated as a secondary crusher, is located between the second and third conveyer belts, we really consider this equipment a part of the coal preparation equipment. With the original arrangement of plates and hammers the capacity of this hammer mill was such that coal was piled up at its inlet when the coal hoist was operated at capacity. Readjustments were made, not only because of the hammer mill's limited capacity with its original adjustment, but also because it was thought that with somewhat coarser coal some difficulties with our grid driers could be eliminated or at least alleviated. After these changes were made, the capacity was increased, but the drier difficulties were not helped to any great extent. It was finally decided to by-pass the hammer mill completely, which enabled us to get better flow through the grid drier with little arching of the coal but, of course, placed a heavier duty on the pulverizing mills.

A pulverized coal system handling wet coal is subject to many ills, and it is difficult to obtain proper flow at many of the points where gravity is the moving force. Very unsatisfactory grinding is obtained with wet coal; after the coal is ground, some of it forms a pasty mass and sticks at almost every conceivable point; a mucky

mass very often collects in the mill, choking up the air passages; vent lines become choked; cyclone separator discharge lines become plugged; transport pumps and lines become plugged; the coal cakes in the pulverized coal bins; arches over the feeder screws at the boiler, causing burners to become extinguished; and even the burner pipes become so choked that in many cases it is necessary to take pipes down for cleaning, as the rapping on the pipe is often ineffective. There is also much difficulty from irregular feeding of the coal to the furnaces, which greatly reduces the furnace efficiency.

The steam-heated grid-type driers originally installed were found to be inadequate for our conditions. As already explained, the delivery of fine coal to the drier resulted in arching and inability to get the coal to flow through the drier. There was also additional trouble due to the pulling along of considerable coal by the air used to remove the moisture. A large amount of air is necessary and while it was put through a cyclone separator, the separation was incomplete, causing a considerable loss of coal. The coal recovered in this cyclone separator was discharged into the hoppers of the transport pumps. There was the additional objection that much of this coal was coarser than desired. Some of the drier grids were removed to better these conditions. While the feeding was bettered, the drying of course was less complete.

Furthermore, the amount of moisture removed was not so great as was necessary for the satisfactory milling and handling of the coal. Failure in this respect caused other means of obtaining the desired result to be considered. We believed that the most reasonable scheme would be that of drying the coal while in a finely divided state in the air circulatory system of the pulverizing mills, as it should give up its free moisture very readily. Due to the relative locations of the mill house and boiler room, it was not feasible to use stack gases for supplying the heat required, or to use the air vented from the mill system for primary air. Accordingly it was decided to heat the make-up air by means of high-pressure steam, so as to obtain the maximum temperature, thereby permitting us to supply the necessary heat with a minimum of air. This permits of using apparatus that is much more compact and reduces to a minimum the amount of fine coal that is lost in the vented air. The mill drier is not effective in drying the coal until it enters the mill and this, of course, does not help the flow of coal to the mill. High moisture, however, has caused no appreciable difficulty in feeding the mills, since the grid driers have been removed. The mill drying system is performing very satisfactorily and has practically eliminated the many annoyances incident to wet coal. In regular operating practise the mill drier has been successful in reducing the moisture content of the coal from 6 per cent entering the mill down to 1.7 per cent leaving the mill.

The air washer as originally installed for use with the grid type driers did not remove the coal dust to a sufficient degree. It was also inadequate when the mill

type drier was put in commission. In order to obtain satisfactory removal, it was necessary to increase both the amount of steam and water used. At the present time, approximately 1150 lb. of steam and 2900 gal. of water are used per hour, with a dust concentration of about 0.8 grain per cu. ft. of air entering the washer, the amount of air handled being approximately 1240 cu. ft. per min.

On the whole, the pulverizing mills have performed very satisfactorily, although, of course, there is considerable wear of the grinding rollers and bull ring of the pulverizing mills, and of the blades and wearing plates of the mill exhausters. These mills, (designated by the manufacturer as of 20-tons per hr. capacity), have pulverized at an average rate slightly in excess of 24 tons per hr. each, the coal leaving the mill having an analysis about as follows:

Moisture.....	0.76 per cent
Volatile.....	25.28 per cent
Fixed Carbon.....	63.76 per cent
Ash.....	10.20 per cent
Sulphur.....	2.02 per cent
Amount through 200-mesh sieve.....	74.2 per cent
Amount through 100-mesh sieve.....	89.4 per cent
Retained on 40-mesh sieve.....	0.4 per cent

At times there has been some difficulty experienced due to coal hanging up in the cyclone separators or in faulty delivery to the hoppers of the transport pumps, because of improper functioning of the flappers of check valves or the choking of vent lines from hoppers to suction pipes of mill exhausters. One other difficulty was the collecting of a mucky mass of coal and water in the chamber of the mill that receives the air returned from the cyclone separator. A muck collecting pocket installed on one of the mills served to alleviate this condition somewhat. However, the better drying obtained when the mill-type drier was installed eliminated all trouble of this nature.

COAL TRANSPORT SYSTEM

There was considerable trouble with the operation of the pulverized-coal transport system when the plant became active. Most of the difficulties resulted in the plugging of transport lines which, being new and rough, were accredited with the responsibility for part of the troubles. The starting up of this system occurred during cold weather and this, in conjunction with the faulty performance of the driers was responsible, no doubt, for the greater portion of the plugging. Also, the size of the hoppers above the transport pumps was thought to be too small for even delivery to the screws of the pumps and partially responsible for the pumps plugging. Accordingly, they were increased in size by adding height with filler pieces having rectangular openings to conform to the hoppers. It was discovered that considerable water collected in the cylinders of the pumps after being shut down several hours. Keeping the pumps drained was the logical answer to this difficulty. Increasing the air pressure on the nozzles

of the pumps also helped to keep the boilers supplied with coal. Later, when the transport lines were worn smooth and the mill drier system was in service, trouble with the transport system practically disappeared.

Coupled with the difficulties of pumping the coal was the difficulty of the sticking of the transport line switching valves. This was alleviated somewhat by applying brass liners to the valves. This has not been an absolute remedy, as it is necessary to operate the valves frequently and even then, to dismantle them occasionally for complete cleaning. A careful analysis of the factors involved is now under way and it is hoped that this will result in eliminating any abnormal routine operation of the valves to prevent their sticking.

PULVERIZING COSTS

The amount of power used in the grinding and transporting of the pulverized coal averages approximately 19.6 kw-hr. per ton of 2000 lb. The expenditure for the maintenance of pulverizing equipment has been approximately 13.9 cents per ton.

BOILER ROOM

The greater amount of effort has been put forth in tuning up and making structural changes in the boiler room to approach or exceed design conditions. While efforts have been made to hasten the process, at this date, February 10, 1928, there are several matters that have not been brought to a satisfactory state.

At the outset considerable difficulty was experienced with poor feeding of the coal due to insufficient drying and condensation on the walls of the bunkers. It frequently became necessary to empty a bunker of the coal which would flow; then have men enter the bunker and scrape down the pasty masses of coal which cling the walls and arch over the feeder screws. This condition was eliminated almost entirely by the mill type drier when it was put in operation. Since our early experiences, No. 1 bunker has been covered with heat-insulating material and an investigation has been made on No. 2 bunker by forcing preheated air over the coal from one end to the vent at the opposite end to reduce the humidity of the air over the coal. The use of hot air results in less condensation on the walls, but also in an increase in the amount of coal lost out of the bunker vent. A combination of heat insulation with the use of hot air would probably give a still better feeding performance.

With the coal-feeding equipment originally installed, it was impossible to reach the maximum designed capacity, part of the fault being insufficient motor speed. However, sufficient coal could not be supplied after the motor speed was increased to that designated. New screws, having a considerably greater capacity, were furnished for one boiler. These screws caused flooding to take place at lower ratings, resulting in very dense smoke and, in one or two cases, in the loss of much coal to the ash hoppers. Also, these screws

had so much capacity that it was considered advisable to abandon them and hob out the original screws. Flooding also took place on these modified screws and to eliminate this, spring-loaded disks were applied to the discharge end of the screws to provide a uniform resistance to the coal being fed. These very successfully reduced the pulsations experienced with the feeders having greater capacity than the original.

The controls of dampers in the various ducts were originally unsatisfactory, in that it was possible for sudden changes to occur if the hand slipped on the operating chains. In the case of the primary air system, a damper got out of control and was responsible for an explosion occurring in the furnace of number one boiler, this explosion resulting in bulging of the steel casing and the bending of several side-wall tubes. By applying worm wheels and sectors to these dampers, the control has been made positive and easier to manipulate.

In order to guard against future explosions displacing the furnace sides, a horizontal steel buckstay was applied around the middle of the furnace for additional strength, as it was assumed that the air and gas passages should furnish sufficient relief for the expansion of the products of combustion resulting from such explosions. The boiler control, also, was provided with some features to eliminate some of the provoking causes of explosions. Furnace contactors were provided to trip out three of the four coal feeder motors per boiler on the occurrence of excessive furnace pressure. Primary air pressure contactors were arranged to trip out the same three feeder motors and to turn on the steam to the burner aspirators on the occurrence of low primary air pressure. The forced draft fan control is arranged to trip if both induced draft fans are tripped. Since these modifications have been made, no occasion has arisen necessitating their functioning.

Changes have been made in the burner design with respect to what is termed the tertiary air, *i. e.*, the heated air which is forced downward around the burner nozzle. These changes have been made with the idea of producing a longer downward sweep of the flame with less and hotter primary air. The present indications are that the new arrangement is very beneficial.

Experimental observations were resorted to in order to obtain a better distribution of air across the furnace. The number of port openings in the front wall was substantially reduced which, by proper selection of the ones to be closed off, improved the distribution, produced greater turbulence, and also made available a higher tertiary air pressure. It was then possible to exercise more control over the tertiary air.

The spring-loaded dampers governing the flow of secondary air to lanes in the front wall have performed unsatisfactorily at times, and it has been necessary to provide hand-control to those governing the air admitted by the four uppermost lanes. It is now considered desirable to have all of the spring-loaded dampers operated by hand from the main boiler floor.

Some difficulties have been encountered with slagging of the lower rows of boiler tubes. This slagging usually occurred after the boiler had been carrying about 400 per cent rating continuously for 48 hours or longer. Little trouble was experienced when less load was carried at night than in the daytime, and it has been noticed that much slag which had accumulated when operating at high rating, fell off when the rating was reduced for several hours. On one of these occasions when a high rating had been maintained for longer than 48 hours, an attempt was made to cause the slag to drop by increasing the excess air, but this apparently had little effect. A shot gun was fired at the slag but was found to have negligible effect. One proposal advanced to prevent this trouble was to remove every other tube in the bottom row of boiler tubes, which would mean that the spacing of this bottom row would then be approximately the same as that of the water screen and, consequently, slagging would be greatly reduced. The boiler manufacturer has recommended against removal of these tubes and, instead, suggests removing every other tube in the lower row and installing deformed tubes which would have a drop of 7 in., thereby accomplishing the same result with no loss in heating surface.

The air heaters are arranged with straight vertical flue gas passages and U-shaped air passages, the air entering and leaving on the same side of the heater, thereby providing very unequal resistances to flow in the air lanes. The result of this was a wide spread in the air temperatures leaving the air heater, there being about 200-deg. fahr. temperature difference between the top and bottom of the duct discharging air from the heater. A deflecting-type baffle was applied to guide the air towards the lanes having the longer paths. Another scheme which was also experimented with, consisted of adding resistance at the air inlet to the shorter paths, the increased resistance to flow of air being obtained by the application of metal strips. The two schemes did materially help the situation and were of about equal merit, although neither attained the desired result. Both schemes are objectionable from the standpoint of power loss caused by the increased duty placed on the forced draft fans. The air heater manufacturer is now taking necessary steps to improve the performance of this apparatus.

The bearings on the primary air and induced draft fans are of the ring oiled type provided with an integral oil cooler built into their bases to eliminate the necessity of separate oil pumps for the circulation of the oil and also to permit the use of harbor water for cooling. There was some trouble from the leakage of water into the oil reservoirs which was eliminated by a slight change in the design of the coolers.

The induced draft fans are of the plate-type because of the high duty imposed by the requirement of handling 135,000 cu. ft. per minute of 450-deg. fahr. gases against a static head of 15.8 in. of water. These fans

have given excellent service except for some slight vibration due to the bearing pedestals being somewhat light. This has been corrected by the application of bracing. Two failures of an induced draft fan motor have occurred, the reason for which cannot be ascribed to overload or faulty control. The first failure was of the north motor on No. 2 boiler. This motor was removed for repairs and was replaced by No. 1 south motor. The repaired motor, when returned, was placed at the former location of No. 1 south motor. Soon after this, the repaired motor failed. This motor was again repaired and has been operating satisfactorily for some time.

Five failures of fin tubes constituting the back furnace wall have occurred. These tubes have all failed in the same manner and almost at the same spot; namely, the outside of the top bend of the rear wall tubes near the sides of the furnaces. In one case, a large bulge was noticed before an actual rupture occurred. The water circulation is to be investigated to determine whether or not there is considerable difference in rapidity of water circulation in different parts of the back wall. The obtaining of this information will no doubt make possible a satisfactory analysis of this condition.

Because of the high rating for which these boilers are designed, it was necessary to supply two 6-in. feed-water regulating valves. It was found that the thermostatic tubes of the feed-water regulators were not sufficiently powerful to operate the valves properly. New pistons were designed by the manufacturer in an effort to reduce the friction which was apparently caused by water flow, since the friction was quite low when no water was flowing through the valves. The new pistons did not prove entirely satisfactory and attention was directed toward the use of hydraulic power utilizing the thermostatic tube to actuate only a pilot valve. As an experiment, one such valve was fitted with a hydraulically operated relay mechanism. The operation was so much more satisfactory that the manufacturer equipped all the regulators with hydraulic operating mechanisms. With this arrangement, there is the additional advantage that the slope of the thermostatic tube can be lessened to speed up the response of the regulator.

Soon after starting the plant, it was determined that the moisture content of the steam leaving the boiler drums was higher than desirable. The boiler manufacturer has developed and installed a new type of baffle which has produced excellent results. The curves in Fig. 1 show, graphically, how great the improvement has been. This improvement should be of much benefit in the maintaining of cleaner surface on the interior of the superheater tubes, since the moisture, of course, carries solids in solution. It also will reduce the duty on the superheater for a given temperature of steam leaving the superheater.

The plant has operated for a large portion of the year 1927, with lower superheat than the design value. It

was held advisable to delay the raising of the steam temperature until other apparatus which would influence the result had been tuned up. Just recently the baffling of the gas passage at the superheater has been changed to give the desired steam temperature. The remaining feature to be reckoned with is the pressure drop of the steam through the superheater, this being approximately 35 per cent higher than expected. Since it reduces the pressure available at the turbine throttle with a given boiler drum pressure, this pressure loss results in a diminution of turbine capacity, thereby limiting plant capacity. The manufacturer has considered the possibilities of reducing this pressure loss to the desired value and is taking the necessary steps to eliminate this difficulty in the near future.

As to the matter of combustion control, several difficulties were experienced in the burning out or breaking down of coils and grounding of wiring. Discharge resistances were provided to lessen the inductive kick from the coils, and wire with varnished cambric insulation was used in the control boxes to

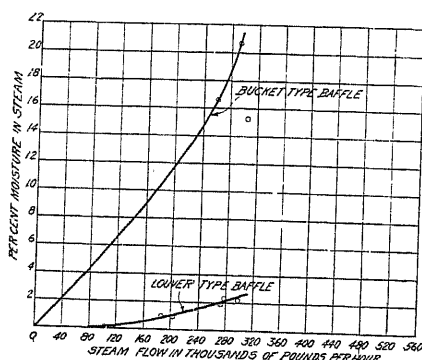


FIG. 1—STEAM QUALITY GOULD STREET BOILERS

withstand the oily atmosphere. Some trouble has also been experienced with the motors in the control boxes grounding, the grounding usually occurring on the brush rigging. Now it is planned to arrange the drive so that the motors may be placed outside. Some gears have been broken, a key sheared, and chains broken, the chains being used to interlock the various drum controllers of the fan motors. Because of the necessity of controlling two 550-hp. pole-changing induced-draft fan motors and two 200-hp. pole-changing forced-draft fan motors, all of the wound rotor induction type, the drive necessarily has quite a task to accomplish, the pole changing feature of the motors contributing some complication on account of the necessity of providing overlap.

The combustion control is normally set to maintain 15 per cent $C O_2$ averaged across the section of the boiler gas outlet. This setting is interfered with to some extent by a variation in feed water temperature. This is particularly so if the two higher pressure feed-water heaters are cut out of the circuit at 20,000- to 35,000-kw. load on one boiler. An attachment has been

designed to quickly correct the meter for this condition and is being installed. The combustion control which we have installed is not suitable for quick changes in load, this having been demonstrated several times. It is our usual practise to operate on semi-automatic control for the quick changes in load which can be anticipated, such as the noontime drop and the morning pick-up.

There are eight 4½-in. high lift safety valves on the drum, and two on the superheater outlet of each boiler, each drum valve having a relieving capacity of 52,500 lb. per hr. and each superheater valve 35,000 lb. per hr. While these valves have not been tested for relieving capacity, two occasions have arisen when the entire plant load has been lost in which the safety valves relieved a total of 380,000 lb. per hr. satisfactorily. One of these occasions was when an air drill penetrated the high-voltage leads from the main generator, causing the differential relays to trip out the oil switch and field breaker, the other when the throttle valve of the main unit became unlatched. The leakage and maintenance of these valves has been very slight and, as a matter of fact, has not been any higher than has been experienced at the Westport plant on 200-lb. pressure service.

There are three ash gates per boiler, 41 in. by 56 in., actuated by oil operated cylinders which at times have refused to move due to friction, distortion, and failure of cast iron plates. In certain places where two ferrous materials rub on one another, one of them has been replaced by non-ferrous material, clearances have been increased, and the cast iron support plates have been reinforced with steel. The result has been almost complete elimination of the sticking difficulties.

TURBINE ROOM

Since No. 1 turbine has been placed in operation, few troubles have been experienced with it. One of these has been the sticking of the primary control valve stem. This stem was made of "Ascoloy" and slides in a Monel bushing. These two metals apparently are not very satisfactory for sliding contact. The Ascoloy stem was replaced with one of medium carbon machinery steel and the bushing enlarged to give a greater amount of clearance, the packing being relied upon to serve partially as a guide. It is contemplated that an Ascoloy stem will again be used but with a cast iron bushing so contained in a steel cage that the cast iron will not be able to break up and go through the turbine. One difficulty which was experienced soon after the turbine was started up the first time was undesirable vibration of the throttle and control valves. This was remedied by the elimination of undue play at certain points and the redistribution of the weight of the pipe, control, and throttle valves among several hangers.

The main condenser, while of somewhat radical design in that the tubes are rolled into the tube sheet at both ends, has given but little trouble. The noticeable leaks which have occurred have been very few. In spite of the fact that the circulating water is high in

salt content, we have been able to maintain the solids in solution in the condensate at a very low value. Computations made before the plant was put into commission indicated that if the leakage was as high as usually obtained with packed tube condensers, it would be necessary to blow down the boilers very frequently, or continuously, in order to maintain the boiler water concentration at as low a value as was considered desirable. The following figures are indicative of the purity of the condensate as usually obtained:

Total solids two parts per million.

Electrical Resistivity . . 1,000,000 ohms per cm-cube. While the dip cells used in determining the electrical resistance of the condensate are subject to erratic behavior at times, the electrical resistance characteristic has been of great help in showing relative performance, because of the rapid change in resistance for a small change in the amount of leakage. Only one leak of consequence has shown up, this one apparently being due to a condenser tube not being rolled in at one end, the flare serving to keep the leakage down for a long time.

The circulating pumps originally furnished required too much power because of the water quantity pumped exceeding the design value and, in order to lessen the load on the motors, it was decided to turn down the impellers.

One trouble which has been had with the steam jet air pump inter-condenser has been the erosion of tubes from the discharge of steam from the pipes used to vent some of the bleeder heaters. Some tubes were removed and a baffle installed to decrease the velocity of the steam hitting the tubes.

The difficulties experienced with the closed bleeder heaters has been confined mainly to those under boiler feed pressure, the most annoying one being the leaking of gasketed joints. Some of this was a result of poor machining. Re-machining and the use of different gasket material has eliminated this annoyance almost entirely. One other source of annoyance has been the leaking of a porous, cast steel, water box which is to be replaced by the manufacturer. The eighth-stage bleeder heater is of the deaerating type and has given no operating troubles, and has delivered water having less than 0.05 cu. cm. per liter of oxygen.

As originally furnished, the evaporator, while its capacity was all that was expected, did not produce a distillate measuring up to the standard required. Considerable experimental work was required before this standard was attained. We were fortunate during this time in having a boiler operating in the old plant supplying steam for heating purposes. Thus, the heating boiler acted as an evaporator and the heating system as an evaporator condenser. The quality of the water obtained in this manner was good, and the amount was great enough for make-up purposes. The changes in the design of the evaporator were completed at about the time that the heating season ended. The

evaporator is now producing water of following quality:

Total solids 3.4 parts per million.

Electrical Resistivity . . 227,000 ohms per cm. cube. With low condenser leakage and water of this quality, we have been able not only to hold the boiler water concentration to a low figure but have not been required to blow down the boilers at all on account of concentration, the concentration not having exceeded 500 parts per million.

While the boiler feed pumps are boiler auxiliaries, we are treating them under the head of turbine room equipment, since they are actually in the turbine room and are connected in between the low- and high-pressure bleeder heaters. The motor-driven boiler feed pumps have given but little trouble structurally. On one occasion there was a cessation of pumping which appeared to be due to vapor binding. This was ascribed to hot water discharged from the evaporator condenser drip pump being fed to the suction side of the boiler feed pump. While there was an economic advantage

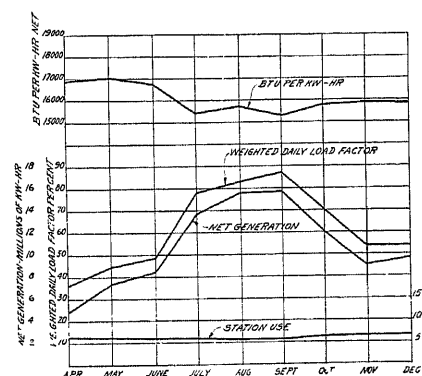


FIG. 2—MONTHLY PERFORMANCE OF GOULD STREET IN 1927

to the scheme from the standpoint of heat efficiency, it was considered to be outweighed by the demand for safe operation and, accordingly, this water was delivered to the eighth stage heater. Since then no further trouble of this nature has occurred. A shifting of the impellers and balancing drum occurred on the emergency steam driven boiler feed pump. This was apparently due to the wearing sleeves turning enough to allow the shift to take place. When repairs were made these sleeves were driven up hard and locked so that this trouble is not expected to occur again.

OVER-ALL PERFORMANCE

Whereas the plant delivered power to the bus for the first time on January 4, 1927, the amount of generation for the first three months was comparatively small, because of the decision to concentrate attention on those details which most affected the dependable operation of the plant. For this reason, these three months have been neglected in drawing up Fig. 2, which graphically illustrates the amount of generation per month, the average weighted daily load factor and B. t. u. consumption per kw-hr. of net sendout. The

amount of generation reflects not only the tuning up of the plant but also the manner in which steam generation at Baltimore is affected by the river flow at the hydroelectric plant of the Pennsylvania Water and Power Company from whom we purchase quite a

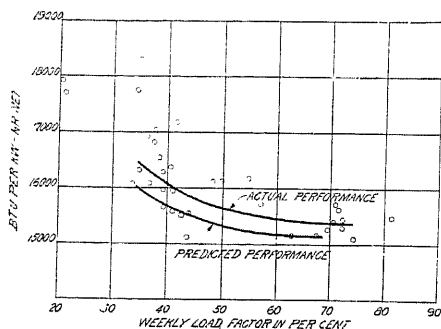


FIG. 3—RELATION OF ACTUAL TO PREDICTED PERFORMANCE FOR GOULD STREET IN 1927

considerable amount of power. Two curves are shown on Fig. 3, one of which is that of the predicted performance of the plant in B. t. u. required per net kw-hr. of station sendout plotted against weekly load factor in per cent; the other curve is that of the weekly performance in B. t. u. actually used, plotted in the same manner. The points plotted for actual performance show quite a wide variation, not only because of the changes being made in the plant during the year, but also because of the fact that there are large coal storage spaces between the point at which the coal is weighed and the point of consumption, a comparatively small error in estimation of the coal in these spaces causing a much larger error in the consumption figures, the greatest error occurring when the consumption is least. It is expected that the installation of automatic coal scales to weigh the coal entering the mills will greatly decrease this error, since the effect of an error

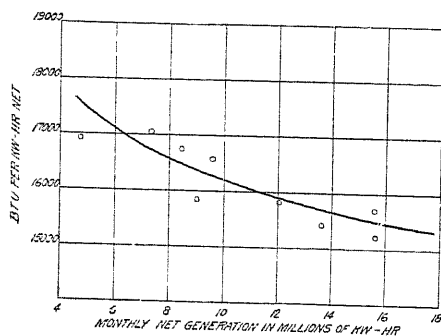


FIG. 4—B. T. U. REQUIRED FOR VARIOUS MONTHLY OUTPUTS AT GOULD STREET IN 1927

in the estimation of the raw coal bunker will be eliminated from the result, the pulverized coal bunkers then being the only storage space affecting the accuracy of the consumption figures. The monthly figures are somewhat more accurate since the amount of coal used

is about four times larger and the error introduced by bunker estimates is thereby made one-fourth as much. It is expected that the predicted performance will be approached very closely.

From this outline, it is apparent that the plant has been subject to the usual minor changes and adjustments during the initial period of service. None of the troubles experienced was unsurmountable and all can be traced to the fact that most of the equipment affected was of the largest sizes that were obtainable, operating in many instances at rather high capacities. This introduced some problems that were entirely new, it being necessary for the manufacturers supplying equipment to do a certain amount of development after their apparatus was placed in service. While such a procedure is necessarily slow, it is felt that the manufacturers affected have made a very satisfactory record in solving their individual problems and in making necessary changes and connections.

The actual performance has approached fairly close to the anticipated, and it is apparent that, when the air heater performance is improved and the effect of the recent increase in steam temperature is realized, the anticipated performance will at least be met and possibly slightly bettered.

Discussion

THE GOULD STREET STATION

(LOIZEAUX, LEILICH, FOLLMER, DANNETTEL, PENNIMAN, AND QUARLES)

BALTIMORE, MD., APRIL 18, 1928

A. G. Christie: There is a number of interesting features in connection with the Gould Street plant.

In the first place, this is the first large American station that has been built on the basis of one boiler to one turbine, and the performance has been quite satisfactory. It is not necessary to have many spare boilers as in some of the older stations. It is quite probable that in new station designs Gould Street's arrangement will be followed.

Another factor of interest is the steam turbine, in which capacity for size of frame is somewhat larger than has been common in the older stations. In other words, for a given size of turbine casing a larger output is obtained than would have been the case a few years ago. This, of course, gives a greater capacity in kilowatts for a given size of installation.

The use of condensers with rolled tubes at both ends is a decided advance. That construction was used in Europe quite a number of years ago but with very short tubes and not with the tube lengths used at Gould Street. As has been pointed out, it was necessary to run a number of tests to determine what would happen to longer tubes and how their expansion could be cared for in order to have the condensers operate satisfactorily.

The type of feed-water heater used is also unusual and apparently quite an advance over former types. The hairpin vertical type of heater takes up little room between the turbines themselves. It is easier to get at than some of the older types.

The air preheaters occupy a large volume. Larger and larger air preheaters will undoubtedly be used as stations grow in size, particularly since their advantages have become recognized.

In Fig. 3 of Mr. Loizeaux's paper, the turbine room is apparently outgrowing the boiler house. By the time the four machines on the present program are installed, the boiler house will be considerably smaller than the turbine room. That suggests

the possibility that larger turbines will be required for later units. Some plants have adhered to the system of having equal sizes of turbines throughout the whole station, but when the possibility occurs of getting extra kilowatts in the same space, it is pretty hard not to add the larger units.

L. W. W. Morrow: I can say whole-heartedly that this is the best group of power-station papers I have ever listened to at the engineering meetings, in that the authors have very frankly told all their troubles and difficulties in connection with the installation and operation of a new power station. Sometimes there is a defensive league, I call it, among engineers whereby everything they do is perfect and they never admit that they could have made an error. It stands to reason that the engineers in this country today are largely responsible for the reductions in the costs of power. It stands to reason that in departing from past practices and in making the great economies that have been made in the last five or ten years in power production, there must occur some errors. There must occur some pioneering engineering developments, and to get full advantage of experiences with new things it is really worth while for the engineers to talk frankly about the new plants.

There are one or two questions that arise in my mind. The use of automatic equipment is to improve station economy and reduce station labor charges. My first question is in regard to the operation of automatic boiler-room control; does it work well? The second question is about labor. How many men per shift are used in this station; and what degree of skill is required for maintenance and for operation? Another question that comes to my mind is the use factor that you can expect out of a one boiler one turbine combination. Are the turbines and boilers equal in reliability from a service standpoint?

The station game today is developing rapidly. We are working water and materials to the full degree they can be worked. The power engineer has to think in terms of basic physics, metallurgy, and chemistry and must be ready to use other fluids and gases than water and air in order to meet the demand for reducing power costs.

H. C. Sutton: In building this plant the engineers, in selecting every piece of apparatus, have taken into account the first cost, interest on the investment, and operating cost, to give us the lowest annual cost.

I note that one feature of the design of the station is rather conservative. It certainly is conservative to select a boiler pressure of 450 lb. I might say that we are interested in the design of a station now to be located at Deepwater, where we will have 1380-lb. boiler pressure.

Another feature that is of interest and unique, is the very large boiler and the admirable design of one boiler per unit. I think that is worth considering in future station design.

Another conservative feature is the low voltage for the station auxiliaries, 440 volts. We, in our recent stations, have selected 2300 volts and 440, except in the smaller stations where we have used 550 volts. Of course, that is a matter of economy, but it has this particular thing to recommend it in design; with the use of 440 or 550 volts you largely limit or eliminate the use of oil circuit breakers which are necessary with 2300-volt auxiliaries. So there is a gain in using the air-type breaker for station auxiliaries that is a very material one, particularly where you have group buses located at various advantageous points throughout the station.

The preliminary design of the Deepwater Power Station to be located opposite Wilmington is interesting. In that station there will be three 12,000-kw., 1200-lb. units, one of these units being used for a power company which will take the steam and also take the electric load from this generator. The other two 1200-lb. units will be the high-pressure units for the two main generator units of the station, the low-pressure unit being 41,000 kw., making a total of 53,000 kw. per unit. The only boiler pressure will be the 1380-lb. boiler pressure, the steam merely

going back to be re-heated before going to the low-pressure unit.

R. L. Thomas: An outstanding feature of the Gould Street Plant is the unusual amount of attention given in design to what has recently been called "dollar efficiency." Other plants have been built during about the same period with lower fuel rates, but in considering those rates there should always be taken into account the cost of the corresponding equipment.

One question occurs to me. The Gould Street loading is such that there has been considerable "banking" at regular intervals throughout long periods. Information regarding banking experience might be of interest, for example, as to how boiler pressure is allowed to decrease during long and short banks, what intermediate firing is done, etc.

J. C. Strott: There is one feature to which I wish to call attention,—that is, the physical layout of the plant itself and of the apparatus in the plant. The plant has been built on about as small a piece of property as is possible without sacrificing any of the operating problems. The outstanding feature in the development of this property was the fact that it was so close to our load centers. The conditions there were very unsatisfactory in so far as foundation was concerned. The foundations, caissons, and footings for the various structures required special considerations. We have made a very economical plant layout when considering the many difficulties.

F. O. Schnure: I want to ask the authors if they have found it necessary to use all of the 53 points on the induced-draft fan control. Another question is—what method is used in grounding the generators, through reactor or resistance?

M. M. Price: Reference has been made in the discussion to the conservative design of this station. From the point of view of 1928, the design is conservative, but the plant was designed and purchased in 1924 and 1925 and the boilers were among the first Babcock & Wilcox boilers, if not the first, to be built for a pressure of 450 lb. with riveted steam drum 60 in. in diameter and with tubes 24 ft. long, and the amount of steam which it was planned to generate in each unit was considerably in excess of the ratings usually considered. The rating demanded of the boilers was so in advance of the practice at the time the boilers were designed that it necessitated redesigning the steam baffles in the drums. This redesign was only carried out through the hearty cooperation of the operating engineers and has led to a distinct advance in securing dry steam at high ratings.

Boilers of higher pressures were considered when the plant was designed but the data on stations designed for such high pressures were not sufficient at that time to justify the selection of a higher pressure, especially when consideration was given to the load conditions under which the station was expected to operate, which conditions still exist.

A. S. Loizeaux: In answer to Mr. Schnure's question, I would say that our Gould St. neutral is solidly grounded. We have recently put a $\frac{3}{4}$ -ohm reactor in the neutral of our 25-cycle system and in the course of time we may do the same thing in our 60-cycle system to reduce the destructive current in the event of short circuits.

Professor Christie was very modest in his discussion. He was called in consultation on a good many matters while we were designing the Gould St. Power House and due to his wide experience in the design of plants in this country and his knowledge of European power houses he was of real help in the design of the Gould St. Plant.

The designing was done in our own engineering department and drafting rooms. The company's construction forces carried out the work. Contractors were called in for a few of the larger elements of the work. One of the more interesting elements was the caisson foundations required. The Foundation Company of New York was employed to obtain the benefit of their experience and use of their supervisory talent. The caisson foundations under the power house are sunk to 50 ft. below mean low water. The caissons supporting the cooling tower were constructed on

shore, like boats, and floated out into place, then sunk and lowered to minus 50 ft. with the open method. Air was then put on the caissons and they were sunk minus 70 ft. with the compressed-air method.

In connection with the water walls of the furnaces, it was unknown what would happen at very high capacities with reference to the production of smoke but we find that there is no excessive smoking at the higher capacities that we have carried. This fact is very fortunate and permits large capacities and overloads on boilers. Mr. Price of the B. & W. Co. and other agents of manufacturers gave us excellent cooperation in the design and construction and entered into the problems involved in a way that insured their proper solution.

A. L. Penniman, Jr.: All of the difficulties experienced in this plant were confined to apparatus that differed in one or more points from equipment for similar purposes that has been in general use. For instance, the relatively poor quality of steam delivered to the superheater was brought about by using drum sizes and baffle arrangements which were normally used in boilers having 20-ft. tubes, and increasing the length of the tubes some 25 per cent. This means that the steam-to-water ratio at the outlet end of the tubes is necessarily very much higher, the velocities are accordingly higher, and the problem of separation in the drum becomes increasingly more difficult. In addition to this the boilers are arranged with furnaces which will permit of their being operated at relatively higher rates of evaporation than has been the general practise.

One question that I had anticipated would be raised in the discussion of this paper, and which would seem to be an entirely logical one is: "Why, after 15 months of operation, do we still have some of these difficulties that have not been ironed out?" This is due in part, at least, to inertia. In the first place when we get into trouble it takes some time for the operating men to form an opinion, after which the chances are probably 5 to 1 that the designing engineers do not agree with them and additional time is spent in the attempt to find a common ground. It is quite probable that the manufacturer is not going to agree with the compromise which we have reached among ourselves, so that additional time is required to arrive at some preliminary decision which frequently does not lead to a correction of the trouble, due to the fact that while we may think we know the physics and mathematics of a lot of these problems, we usually find after we get the final solution that there were many unknown factors. However, we must remember that the plant is doing substantially what it was designed to do. The figures in the curve of the paper were made before the steam temperature was raised. The air heaters have failed to meet the anticipated performance given by the manufacturer simply because laboratory experiments indicated higher rates of heat transfer than we have been able to obtain in practise. At present there seem to be very definite indications that the heat lost by radiation from the steam generating units is greater than was anticipated. On the other hand the heat-absorption rate of the boilers is apparently somewhat better than we had anticipated so that the curve, which shows a variation of about $2\frac{1}{2}$ per cent from the designers' anticipated results, can be accounted for as being due to poor performance of the air preheater and to low steam temperature.

Another question that I had anticipated is: "What conclusions have we been able to draw from the operation of this plant that might guide us in future additions or in the building of another plant?" In the main there are three general points; one is, if you are going to use pulverized coal prepared by a central system, do not try to start up in cold weather. The humidity is so much higher in cold weather that the tendency to gum the mills transport system, and ground-coal bins, is very much greater than in the summer, and is very likely to be further aggravated during the time necessary to get the coal-drying apparatus tuned up. We had numerous cases of the plugging of transport pumps and transport lines, the mudding up of the

return air lines from the cyclones to the mills, and the mudding up of the mill cyclones. The switching valves in the coal transport lines stuck frequently. The furnace feeder screws mudded up and the coal arched over the throat of the feeders. At times it was hardly possible to deliver enough coal to the furnace to keep up steam pressure on the boiler. As soon as we were able to dry the coal properly all of these difficulties disappeared.

Secondly, a great deal depends on the proper method of drying coal. Our experience with grid driers was most unfortunate. As a matter of fact they simply refused to dry at all, and in addition so impeded the flow of coal to the mills that it was necessary to remove a large percentage of the grids in order to get coal through them at a sufficient rate. We have now been using the mill-drying scheme for some five or six months. We are feeding air heated to slightly less than 400 deg. Fahr. into the mill with the return air, and venting a comparable amount of air from the system at the air-outlet side of the mill cyclone. There have been no troubles from this system. The reduction in temperature of the air is very rapid due to the evaporation of the moisture in the coal. Apparently the air temperature drops from 400 deg. Fahr. to less than 165 deg. Fahr. in the first 12 or 14 in. of travel of the air, while the temperature in the mill does not exceed that reached without air drying by more than 5 deg. The method used to control the amount of heat to be added is to vary the amount of hot air applied so as to maintain a fairly constant temperature of the coal-air mixture leaving the mill.

The third point is the question of steam temperature. I am rather convinced that there is no reason why in the next installation we should not go to 800 or 825 deg. Fahr., for the steam temperature leaving the superheaters, or for that matter why this higher temperature should not be generally used. This is the greatest opportunity for gain in economy, and at a relatively small expenditure, that is presented to the designer at the present time. With the present inter-deck superheaters we frequently get rather high temperatures with no serious effect on the superheater, and no apparent effect on the turbine. We have radiant-heat superheaters installed in the bridge walls in some of our stoker-fired furnaces at Westport, which have been in service for nearly five years, operating with metal temperatures up to 1100 deg. Fahr. They are in series with convection superheaters at the top of the first and second passes of the boilers, and maintain a very uniform steam temperature over quite a range of rating. The radiant-heat superheaters are not fitted with any type of flooding device and the boilers are banked frequently for protracted periods. If these superheaters will stand this sort of punishment, I can see no reason why we should not approach the same condition at Gould Street, and I anticipate raising the steam temperature as soon as we have some of the other operating problems cleaned up.

F. W. Quarles: Mr. Morrow asked how many men we require. I believe they average about fourteen per shift. The use factor of the boilers at the present time has been governed considerably by some of the changes that have taken place in the plant to rectify certain conditions. I think that at this time we cannot draw any satisfactory conclusions as to the use factor. Mr. Morrow also asked about the maintenance of the automatic control. So far the maintenance of the automatic control has been comparatively small on standard equipment. Where we have used new schemes we have got into difficulties, but in the case of the combustion control which is composed of standard pieces of equipment, it has had a very large job to do, much larger than in the usual plant. That is, on the induced-draft and forced-draft fan controls there are four drums that must be operated by this control, and there has been occasional trouble with interlocks which have caused breakage of some chains and other parts, but with the improvement of the interlocks, and the strengthening of certain parts, maintenance of this control should be cut down materially.

There was a question raised by Mr. Thomas about banking.

I don't believe we have any figures that we could furnish at this time regarding the amount of coal required in banking. We don't have any easy means of measuring it at the present time. However, it requires, about once every four hours, the use of burners to bring the pressure back to normal, having allowed the pressure on the plant to reduce about 100 lb., the plant being shut down completely.

Mr. Schnure asked about the necessity of using the 53 points on the control of the induced-draft fans. We feel, in the case of this plant, that it is necessary to have a large number of points on the control of the forced and induced-draft fans because

of the large range in speed that is required. In other words, in order to keep large fluctuations from occurring in the CO₂ value it is necessary to make small changes of air flow. Now in this case the adjustment is made by means of speed of the fans and very little by means of dampers. The only damper control is on the induced-draft fan and that damper control is of very little effect in the range where the motors are running. Most of its effectiveness is confined to the period when the boiler is running on natural draft.

The grounding of the neutral of the main generators is solid; there is no series reactor or resistance used.

The Conowingo Hydroelectric Development on the Susquehanna River

BY ALEX. WILSON 3RD¹

Associate, A. I. E. E.

Synopsis.—The Philadelphia Electric Company, through its subsidiaries, has just completed construction of the Conowingo dam and powerhouse to develop the fall of the Susquehanna River from the tail-race of the Pennsylvania Water and Power Company's dam at Holtwood, Penna., to a point within four mi. of tidewater. This project ranks as one of the largest hydroelectric developments in the United States and is exceeded in size by the Niagara Falls development only. The speed of its construction, requiring less than two years from the start of construction operations to regular operation of the first units, is an outstanding achievement.

In an average year, 1,250,000 kw-hr. will be delivered in Philadelphia at 220,000 volts, from the initial installation of seven 54,000-hp. water-wheel units, (ultimately to be increased to 11 such units), resulting in a saving of more than 750,000 tons of coal annually.

These water-wheels and generators, together with the 27-ft. diameter butterfly valves installed as head gates, are the largest from the standpoint of physical dimensions yet constructed.

The concrete dam of gravity type, 4630 ft. long, develops a normal head of 89 ft., and has created a lake 14 mi. long. The spillway section, 2385 ft. long, has been designed to pass a maximum flood of 880,000 cu. ft. per sec. and is surmounted by movable crest gates for maintaining a constant head-water level.

Relocation of 16 mi. of railroad together with many State and County roads and bridges was required in the acquisition of lands for the reservoir.

Unusual features of the design and construction of the dam and power station together with a general description of the entire project, are included in this article.

THE Conowingo Hydroelectric Development, with an initial installation of 378,000 hp. in seven main units ultimately to be increased to 594,000 hp. in eleven units, ranks as one of the largest hydroelectric projects in the United States, as shown by the following table giving installed capacity in other large plants.

Plant	Owner	Installed hp.
Niagara Falls	Niagara Falls Power Company	425,500
Conowingo	The Susquehanna Power Company	378,000*
Muscle Shoals	United States Government	260,000*
Holtwood	Pennsylvania Water and Power Company	158,000
Keokuk	Mississippi River Power Company	150,000

*Initial Installation.

In the average year, the initial Conowingo plant will deliver 1,250,000,000 kw-hr. to Philadelphia and interconnected districts, resulting in an annual saving in coal of more than 750,000 tons.

From the standpoint of speed of construction, Conowingo is an outstanding achievement in the history of projects of similar size. Construction work was started March 8th, 1926, under Federal License approved February 20th, 1926, and on March 1st, 1928, less than two years after starting construction, the first units were placed in regular operating service.

It is the purpose of this paper to outline the general features of the project and to describe particularly the design and construction of the dam and power house, and hydraulic equipment.

THE SUSQUEHANNA RIVER

With the exception of the St. Lawrence, the Susquehanna River basin is the largest and most important

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on the Atlantic Coast. Its total area of 27,400 sq. mi. includes 47 per cent of the total area of the State of Pennsylvania, 13 per cent of the total area of the State of New York, and two per cent of the total area of the State of Maryland, and extends north almost to Utica, N. Y., and west beyond Altoona, Pa.



FIG. 1—MAP OF AREA DRAINED BY THE SUSQUEHANNA RIVER

The head waters of this river system are on the elevated plateau which separates the waters which flow south and east into the Atlantic streams from those flowing north and west into the Mississippi, St. Lawrence, and Great Lakes.

From Northumberland, situated at the junction of its east and west branches, the river has a fairly uniform grade of two and one-half ft. per mi., except for local rapids between the Muncy Dam and Conewago Falls, near York Haven. Below, or in the lower 40 mi. of its course, the slope increases to an average of five ft. per mi. to tidewater, and the width of the river becomes contracted, narrowing into a gorge which, in places, is reduced to a width of two-tenths to one-half mi. In the last 27 mi. of its run, the river drops from an elevation of 225 ft., with an average slope of 5.6 ft. per mi., causing a swift current which has worn a low water channel of great depth in many places.

Along this lower section, the river has cut its way through a range of table land, and its bed is walled by steep, rocky bluffs on both sides, affording excellent

Susquehanna have been taken since 1891 at Harrisburg, which shows that, like all other Pennsylvania streams, its natural run-off varies widely both from day to day or week to week and from season to season.

High water frequently occurs in January from melted snow. Floods accompanied by ice gorges occur usually in March and result in a high water level, although with a lesser volume of flow than at times of clear water floods caused by heavy rainfalls, occurring over the whole or a portion of the water shed as late as June. In late summer or fall, periods of low water are frequently noted.

During the past century, there have been several great floods in this river, the most notable of which was that of June, 1889, which was coincident with, although not caused by, the Johnstown Flood, and which prob-

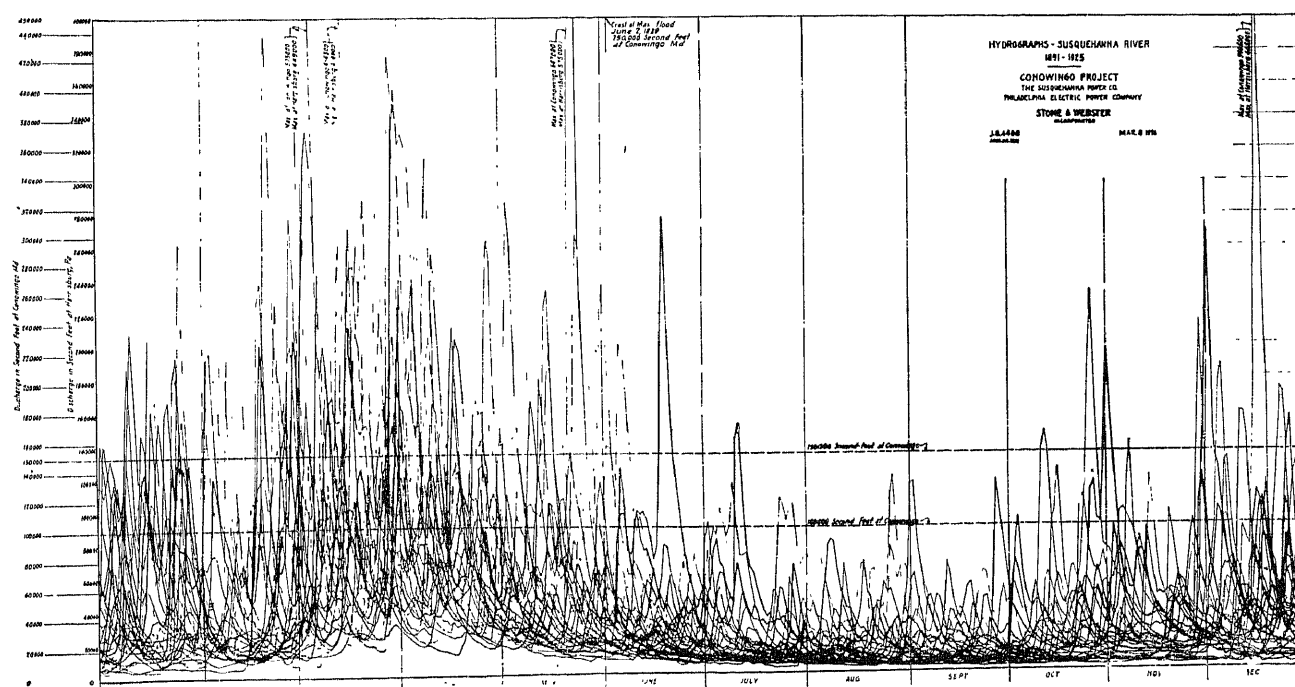


FIG. 2—HYDROGRAPHS—1891 TO 1925 INCLUSIVE

foundation for water-power developments. A portion of the fall in this section has been developed by the Pennsylvania Water and Power Company's dam at Holtwood, Pennsylvania. The Conowingo Dam will utilize the head from the Holtwood tail-race to within four mi. of tidewater.

The annual precipitation over the area drained by this great river, according to records of the United States Weather Bureau, varies from 31.4 in. to 44.3 in., with a mean of 39.4 in.

The run-off, which eventually finds its way to the sea through the Susquehanna River, varies from 16.6 in. to 29.1 in. and averages 55 per cent of the rainfall. The run-off is at a minimum in August, September, and October, during which months it ranges from 5 per cent to 30 per cent of the rainfall and averages about 15 per cent. Reliable official records on the flow of the

ably exceeded any flood that ever occurred in this stream. It is estimated that during this flood, the rate of flow reached a maximum of 730,000 cu. ft. per sec. A minimum discharge of 2200 cu. ft. per sec. was recorded at Harrisburg in 1909.

Due to the frequent recurrence of low-flow periods, which limit the amount of firm power available, large scale power development was not economically feasible until electric demand in nearby centers served from steam driven generating equipment, had become capable of absorbing the hydro power available during high-flow periods. This condition is met by the load of the Philadelphia Electric Company System and its interconnections with other utilities. Thus the Conowingo site, with a firm power value of but 30,000 kw., will initially deliver in Philadelphia 1,250,000,000 kw. hr. annually, resulting in an annual saving of more than

750,000 tons of coal and with the present shape of the daily load curve of the Philadelphia Electric Company System, the Conowingo plant can be relied on for a minimum peak capacity of 180,000 kw. which ultimately would otherwise have to be provided in steam plant capacity.

CORPORATE ORGANIZATION

As the Philadelphia Electric Company will use practically the entire output of the Conowingo Development, it was necessary that it should control the operation of the plant. Its charter, however, does not permit it to operate or hold title to property in Maryland. These requirements were met by the organization of three subsidiary or otherwise controlled corporations, as follows:

pany. As set up, therefore, the Conowingo Hydroelectric Development has been made by and for the Philadelphia Electric Company, and is being operated as a part of that company's system.

RELOCATION OF HIGHWAYS AND RAILROAD REQUIRED

The Conowingo Dam and Power House are located in Cecil and Harford Counties, Maryland, about six miles from the Mason and Dixon Line and four and one-half miles upstream from the town of Port Deposit. The reservoir above the dam has an area of 14 sq. mi. and extends above the dam a distance of 14.6 mi., of which 9.3 mi. are in the State of Pennsylvania. Relocation of 16 mi. of the Columbia and Port Deposit Branch of the Philadelphia, Baltimore, and Washington Railroad Company operating on the left bank together

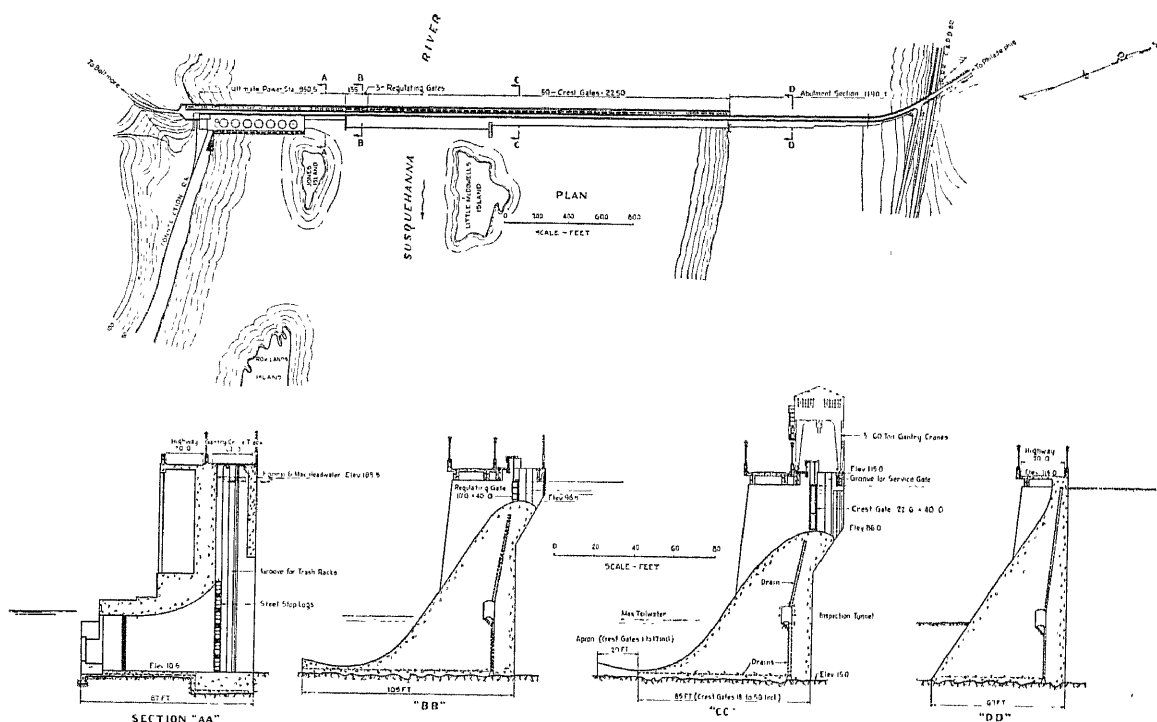


FIG. 3—GENERAL PLAN AND SECTIONS—CONOWINGO DAM

The Susquehanna Power Company, incorporated in Maryland, to hold title to all the physical properties of the project located in that State, including the dam, power house and tail-race, and portions of the reservoir and transmission lines.

Philadelphia Electric Power Company, incorporated in Pennsylvania, to hold title to all physical property of the project located in Pennsylvania, this being principally lands for the reservoir and the greater portion of the transmission lines.

The Susquehanna Electric Company, which has leased for the term of the Federal License the properties of the Susquehanna Power Company in Maryland. This subsidiary under contract with the Philadelphia Electric Company operates the plant and sells the generated energy to the Philadelphia Electric Com-

pany. with numerous County and Township roads and one State road, including a steel-bridge crossing the river at Conowingo, Maryland, two mi. above the dam, were made necessary by the impounding of the waters in the reservoir.

The total of these items involved a considerable amount of work. A new highway bridge with 20 ft. wide roadway, supported on the structure of the dam and power house has been provided together with 4.37 mi. of 18 ft. wide concrete highway connecting the new bridge with the existing State road on either side of the river. The relocation of the railroad on the left bank made necessary the construction of a double track road-bed from Port Deposit, Maryland, to Fishing Creek, Pennsylvania, and involved 1,460,000 cu. yd. of excavation (including borrow) 900 ft. of tunnel,

42,000 cu. yd. of concrete masonry in bridges and culverts and the laying of 20 mi. of single track.

MAXIMUM POOL ELEVATION

By agreement with the Pennsylvania Water and Power Company whose dam is located at Holtwood, Penna., upstream from the Conowingo Dam, a normal and maximum pool elevation, 108.5 ft. above sea level, has been adopted. At this elevation, the impounded waters of Conowingo Dam will be backed up over a portion of the Holtwood Plant's tail-race, which has not yet been excavated but which, if excavated, would result in increased head and power at the Holtwood plant. It was mutually agreed that this additional head could be developed more economically at Conowingo Dam, and arrangements were made, therefore, that the Conowingo pool should be maintained at the above elevation, with the Holtwood Company sharing in the gain accruing from the increased head.

SITE OF DAM

At the site of the Conowingo Dam, the hills on either side of the river form natural abutments. The river bed and its banks, to a height well above the reservoir level, are of igneous formation. Core borings, drilled along the line of the up-stream face of the dam to depths varying from 5 ft. to 100 ft. below the rock ledge, all showed firm hard rock for their entire length.

On the left or Cecil County shore, ample space with rail connection to the Columbia and Port Deposit Railroad was available for the erection of construction camp and plant and for storage of materials.

As the main channel of the river ran along the Harford County shore, the power house has been located at this end of the dam. Space for construction plant at this side was somewhat limited by the rather abrupt rise of the river bank. To provide transportation facilities to the power house site, a single track railroad connecting with the Penn. R. R. in Havre de Grace was constructed on the tow-path of the old Tidewater Canal which formerly operated on this bank, but which has been abandoned since the latter part of the nineteenth century. A freight classification and material storage yard was established on Giles Island, located on the route of the construction railroad about three mi. below the dam.

DESIGN OF DAM AND HEADWORKS

The dam is of solid concrete masonry construction, designed as a gravity section. Its total length, 4648 ft., includes the power house headworks, 950-ft. long and 2385 ft. of ogee type gate-controlled spillway section. To collect seepage water under the dam, and prevent excessive uplift, a longitudinal drain was installed on the foundation ten ft. six in. downstream from the face of the dam. Cross drains spaced 45 ft. on centers connect this drain to tail-water at the toe of the dam. Riser drains at all vertical construction

joints connect the bottom drains to the inspection tunnel. To reduce seepage through the vertical construction joints, copper sealing strips were installed near the upstream face of the dam. Grout holes located two ft. inside the upstream face of the dam were drilled in the foundation to a depth of 20 ft., at 10-ft. intervals and grouted under 25 lb. pressure to form a cut-off wall against seepage through the foundations.

The dam and power house are founded on rock at an average elevation of about 12 ft. above sea level for the dam and 7 ft. for the power house. Due to folding and metamorphic intrusions, the rock surface presented, after removing all overburden and rock that could be barred loose and cleaning out all seams, was very rough and irregular and thus provided excellent bonding for the structures. Soft seamy rock was encountered in but two sections requiring more than removal of loose material to secure a satisfactory foundation.

The overhanging crest is an unusual feature of the spillway section. This permitted a curved surface, approximating the lower nappe of an overflowing stream of the depth of 22½ ft. to be formed without increasing the width of the section beyond that required for stability.

The crest of the main spillway is fixed at elevation 86 and is surmounted by 50 Stony type movable crest gates, each 22.5 ft. high by 41 ft. wide, operating in guides provided in concrete piers on the dam. Three regulating gates, each 10 ft. high by 41 ft. wide, have been provided adjacent to the power house on a fixed crest at elevation 98.5, for use in finer regulation of the pool level. In the design of the spillway, an allowance of 4000 lb. per linear foot was assumed for ice pressure at the water surface. A compressed air system, discharging air below the water surface upstream from the gates, has been provided to prevent formation of heavy ice against the gates. The above pressure was considered, therefore, to be concentrated at the piers. Electric heaters have also been provided to keep the gate guides free from ice. The gate piers, spaced 45 ft. on centers, continue up above the pool level, and support a runway at elevation 115, extending along the spillway section and power house headworks from which three electrically operated gantry traveling cranes operate the crest and regulating gates as well as the sectional head gates and trash racks on the power house. The gate piers also support the highway bridge, which has replaced the old Conowingo bridge, inundated in the reservoir.

The spillway section for the three regulating gates and 17 crest gates has been provided with a 20 ft. wide apron curving up from the toe of the dam to an angle of 12½ deg. with the horizontal in order to prevent erosion at the toe of the dam. Tests conducted at Worcester on a model of the spillway and apron indicated that the maximum erosion would take place about 150 ft. beyond the toe and might reach a depth of 25 or 30 ft.

below the river bed. These tests also indicated that practically no erosion would occur directly at the end of the apron.

The power house headworks section was designed as a gravity section to be stable, independent of the power

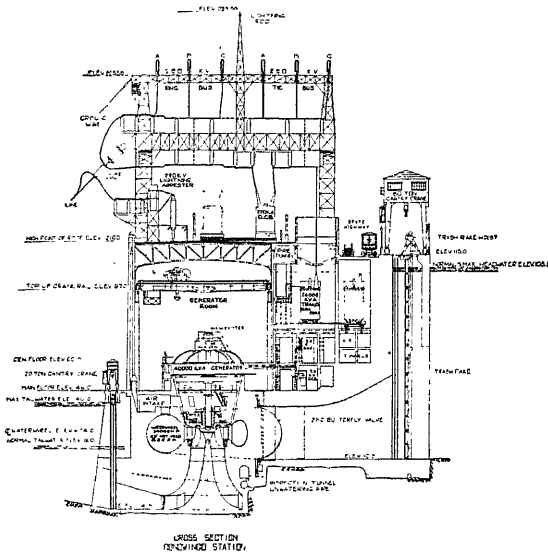


FIG. 4—CROSS-SECTION OF POWER HOUSE

house structure. The heavy bottom slab forming the floor of the intakes has been keyed into the foundations and the walls and roof of the intakes tied to this with heavy reinforcing to resist the uplift pressure on the intake roof. At the upstream face of the head works section, a reinforced concrete curtain wall extends to a depth of 40 ft. below the surface of the reservoir for the purpose of preventing ice and trash from entering the intakes below.

POWER HOUSE STRUCTURE

The substructure of the power house, designed to meet the requirements of the waterways required by the

hydraulic units and to support the superimposed loads of the water-wheels and power house superstructure, was constructed of reinforced concrete. A maximum depth of foundation excavations to elevation minus 20.5 ft. was required at the hydracone draft tubes of the wheels. Where spreading type, draft tubes were used on three of the units, excavation was carried to elevation 16.5 ft. below sea level. Weep-holes were provided in the floors of the draft tubes to relieve excessive uplift pressures. At the downstream face of the substructure, the supporting piers have been extended to provide guides for draft tube ston logs.

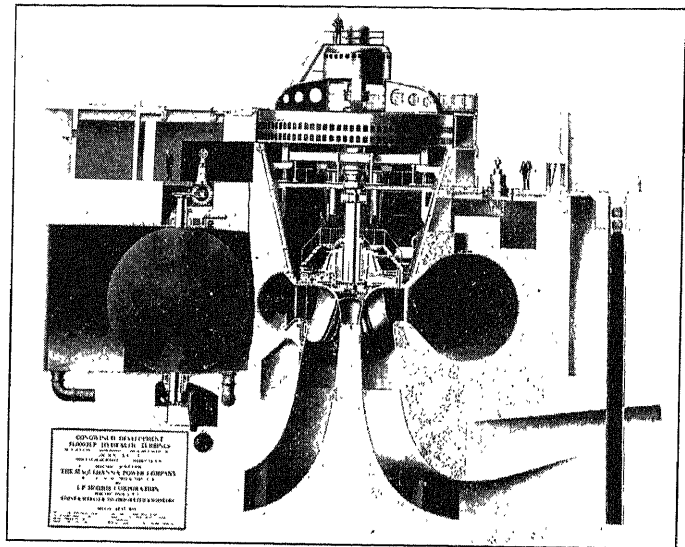


FIG. 5—SECTION THROUGH WATER WHEEL UNIT

Upstream from the units and below the level of the scroll cases, is an inspection tunnel from which access is afforded to each draft tube and to the butterfly valve thrust bearings and the valve in the unwatering system. Seepage through construction joints in the

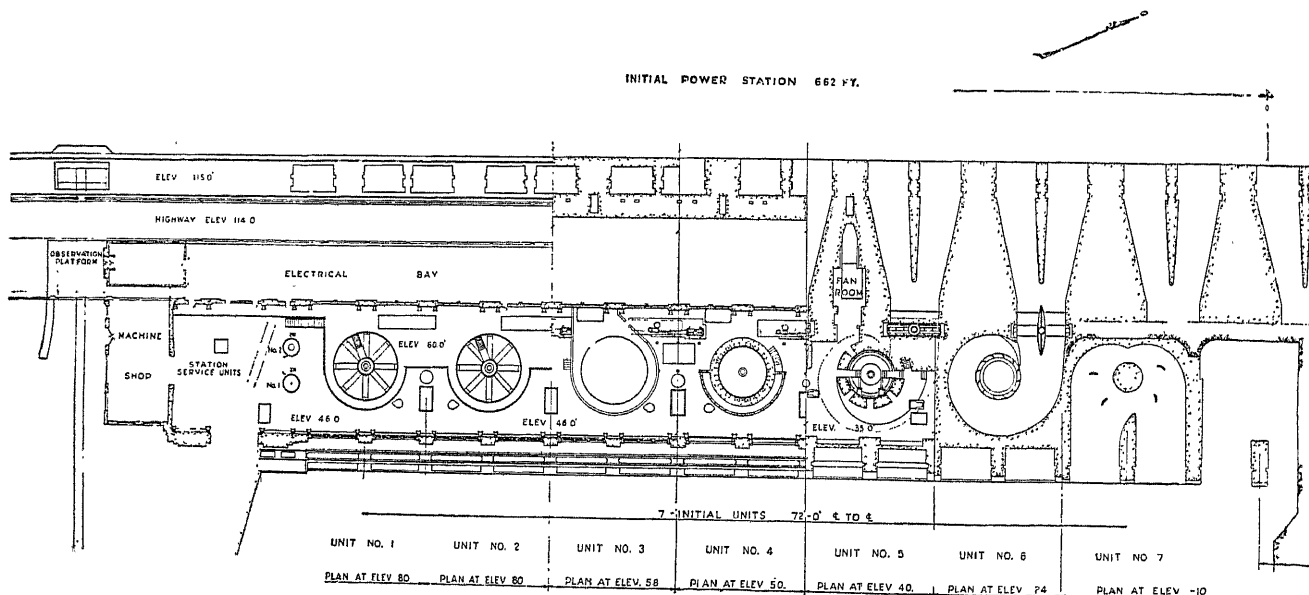


FIG. 6—PLAN OF THE CONOWINGO STATION

substructure and head works is collected in a trench running in the inspection tunnel and drained to a sump at the west end of the power station, where two small pumps are provided. Below this tunnel is a 42-in. cast iron unwatering header draining to a drainage pump of large capacity located at the shore end of the station served by two 15,000-gal. per min. pumps. Each draft tube, scroll case, and intake upstream from the butterfly valve is connected to this unwatering header through suitable valve control piping so that this central pumping installation can be used to unwater any one unit if desired. The main power station superstructure of the initial installation includes the generator room, which is about 70 ft. wide by 75 ft. high by 650 ft. long. The electrical bay between the generator room and headworks is a two story building containing the 13,800-volt bus and switch compartments. Compartments for step-up transformers are located on the roof of the electrical bay, together with the main control room and the station service control room from which windows afford a direct view of the generator room. The 220-kv. switching station is located on the roof of the generator room. The frame of the power house superstructure is designed of reinforced concrete on a structural steel frame with reinforced concrete roof carried on steel trusses. All loads imposed by the switching station on the roof are carried down to the substructure through the steel columns heavily reinforced with concrete. The loads of the two 150-ton cranes are carried on separate steel columns which are tied in with the building columns for the lateral support only. A dismantling area designed for uniform load at 2000 lb. per sq. ft. has been provided at the shore end of the power station for the purpose of assembling such large parts as the generator rotors and water-wheel runners. A standard gage railroad enters the building at this point and also affords ready means of delivering material to the machine shop located beyond the generator room. An office bay has been constructed between the power house and shore and is equipped with an elevator operating between elevation 35 and the reception room, at the elevation of the highway bridge.

HYDRAULIC EQUIPMENT

Initial installation provides for seven 54,000-hp. Francis runner, vertical-shaft water-wheels, operating under normal head of 89 ft. and at 81.8 rev. per min. each direct connected to a 40,000-kv-a., three-phase, 60-cycle, 13,800-volt generator. These water-wheels, generators, and valves are the largest in physical dimensions constructed to date.

There are also two 1900-hp. station service units.

The shape of the intake was determined largely by the use of butterfly valves as head gates for the water-wheels, permitting the intakes to be designed with a wide entrance near the bottom of the river and low entrance velocity, which is accelerated uniformly to a

maximum in the scroll case. The intake of each main unit is divided into two sections by a vertical reinforced concrete wall which extends to within 22½ ft. of the center line of the butterfly valve. Guides for steel head gates and sectional trash racks have been provided at the entrance, together with guides for a mechanical trash rake which operates on rails on the headworks. Head gates and trash racks are operated by the same gantry cranes described for the crest gates.

Seven water-wheels are connected to generators of different manufacture. All water-wheel runners have been designed with the same clearance dimensions and the same number of speed-ring vanes and guide vanes. The waterways have the same general dimensions and the valve control mechanism and various auxiliaries are alike. As the runners of the different manufactures are interchangeable, only one spare runner is required. Four water-wheels have draft tubes of the hydracone

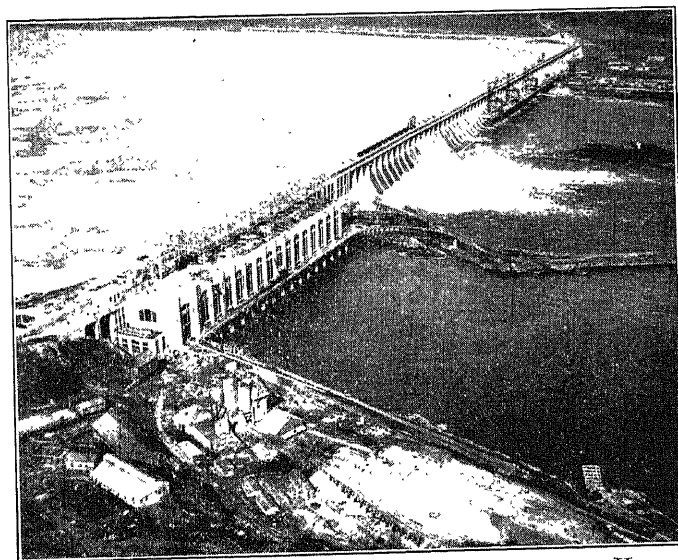


FIG. 7—AERIAL VIEW OF COMPLETED DAM AND POWER HOUSE, TAKEN FEBRUARY 1927

type. Spreading draft tubes have been constructed for the other three water-wheels. The governors are of the actuator type with flyballs driven through gearing from the main shaft and are operated by oil pressure cylinders. There is one oil pressure system for each pair of units. An oil storage and purification system has been provided for all of the governors and bearing oil of all units, including station service units. With each main water-wheel unit, a 27-ft. diameter vertical shaft, butterfly valve, complete with operating equipment, oil pressure system, and accessories, has been installed at the water passages to the runners. These valves have a cast steel housing and a wicket of cast steel, a forged steel shaft and a plate steel penstock liner, extended 12 ft. upstream in the intake passage. These valves are operated by oil pressure from a central oil pressure system. All butterfly valves and the plate steel scroll cases to which they are attached have been furnished by the same manufacturers as the

respective water-wheels units on which they have been installed. The weight of the rotating elements, together with hydraulic thrust, is carried by the thrust bearings on top of the generators. These bearings are supported by bracket arms extending radially from the structural steel pit liner, which also supports the stator of the generator. Both spring-type thrust bearings and Kingsbury thrust bearings have been used.

RIVER DIVERSION AND CONSTRUCTION METHODS

At the beginning of the work, a progress schedule was carefully worked out to determine the progress necessary to be made by the various operations of the work to coordinate these operations with the scheme of river diversion. This schedule contemplated operation of the first two units on June 1st, 1928. Construction progress, however, was considerably better than scheduled with the result that two units started commercial operation on March 1st, and a third unit, a few days later.

In the low-water season of 1926, a cofferdam of the puddle-chamber type was constructed enclosing the power house and west branch of the tail-race, an area of about 14 acres. The top of this cofferdam was built to elevation 42, at which elevation it was estimated that it would not be topped by flood of any volume less than 350,000 cu. ft. per sec. so that work on the heavy excavation of the power house foundations and draft tubes could reasonably be expected to proceed without interruption by floods in the Spring of 1927. Simultaneously with the construction of the power house

the power house cofferdam and, of course, topped the spaced crib cofferdam on the other side of the river. As the foundations for the dam had been completed in this area with alternate spillway sections each including two bridge piers poured to a height above the river level, it was not necessary to unwater this cofferdam again after the flood has subsided.

During the winter and early spring of 1927, the pour-

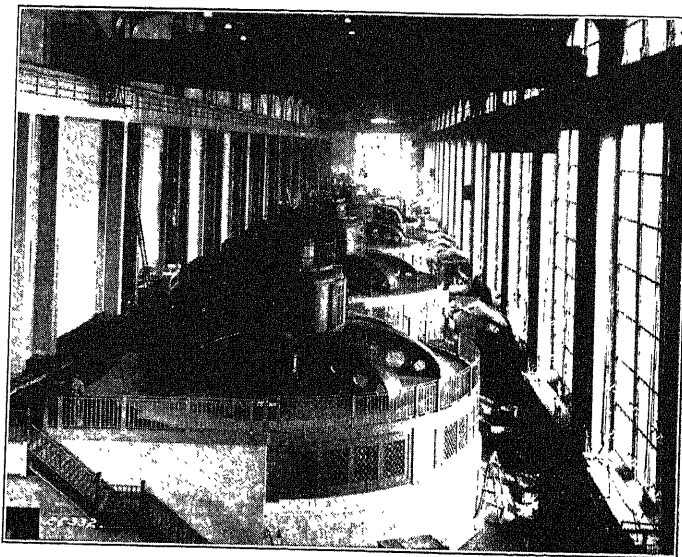


FIG. 9—GENERATOR ROOM—CONOWINGO STATION

ing of the pier sections was completed up to and including the highway bridge, leaving intermediate sections 38 ft. wide at the level of the foundation (elevation 22) to provide for the diversion of the river during the summer of 1927. Likewise the power station headworks was completed during this period up to an elevation well above flood levels.

As soon as the spring floods of 1927 had sufficiently subsided, the cofferdam was extended from the last completed spillway section to the power house headworks, and by September, the foundations of the dam had been completed in this last cofferdam and the alternate sections poured above the elevation of the top of the cofferdam. With the removal of this cofferdam, twenty 38 ft. wide notches in the spillway, together with eight 10 ft. high by 18 ft. wide sluices through the spillway, were taking care of the river flow.

Final closure of the notches was commenced early in October, 1927. The easterly ten notches were first brought up to elevation 30, and the west ten to elevation 35. These two groups, with a 5-ft. difference in bottom grades, were then raised alternately in 10-ft. lifts, thus providing 5-ft. flow through ten openings in addition to the flow through the eight sluices. In the actual closing of the water-way at each 38-ft. opening, a steel and timber flap gate hinged at the top from the adjoining spillway sections was used. The gantry cranes provided for the crest gates were used to handle these flap gates. With the raising of the notches and corresponding rise of the headwater level, the discharge

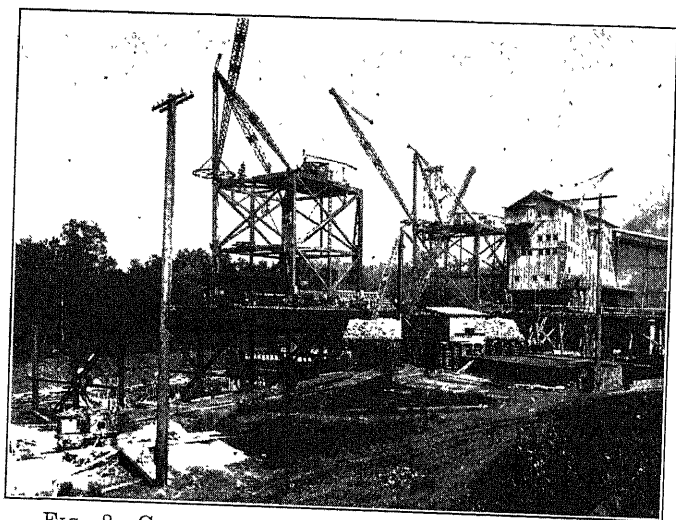


FIG. 8—CONSTRUCTION PLANT—EAST SIDE OF RIVER

cofferdam, another cofferdam of the spaced crib type was constructed from the Cecil County shore, extending to within approximately 700 ft. of the power house cofferdam. About the middle of November, a flood of 350,000 sec. ft., the greatest November flood that has been recorded for the Susquehanna River occurred. The head water elevation rose to within a few inches of the top of the sand bags which had been placed on

capacity of the eight sluices increased so that finally, when the notches had been raised to about elevation 50, the discharge from the sluices was equal to the river flow and the closing of the notches was completed without the use of the flap gates.

After the concrete in the notches had been completed to crest elevation, final closure of the eight sluices was made by lowering specially designed, reinforced concrete gates, weighing 75 tons each, and then filling the sluiceway opening with concrete.

Closure of the notches was hampered through November and December, 1927, by high water. Favorable flow conditions occurred in January, however, permitting completion to crest elevation on January 16 and on January 17, 1928, the sluiceway gates were dropped, making the final closure of the dam.

For the construction of the dam, a steel work trestle with deck at elevation 60 was built on the toe of the dam. Three self-propelled, electrically-operated gantry travelers, each equipped with a 15-ton steel derrick and concrete elevator, were used, the travelers operating on rails at the sides of the trestle deck and being designed to allow clearance for cars operating on the three standard-gage tracks, also provided on the trestle deck. The concrete mixing plant for the dam consisted of four mixers of 2-cu. yd. capacity each, and was so designed that the mixers discharged directly into hoppers mounted on cars on the work trestle. Gasoline locomotives were used to transport the concrete from the mixing plant.

In the construction of the power house and headworks, a central concrete mixing plant consisting of two mixers of two cu. yd. capacity each, was used. Placing of concrete was accomplished with 16-in. chutes from wood towers 250 ft. high. Guy derricks were used in

handling forms and other materials. Erection of structural steel was accomplished by use of a traveling derrick mounted on the headworks. This traveler was also used to erect the steel arbor structure of the 220-kv. switching station on the roof of the generator room. The following quantities involved in the construction of the dam and power house will be of interest:

Cofferdam Crib.....	4,250,000 cu. ft.
Rock excavation, including tail-race	348,000 cu. yd.
Forms.....	3,850,000 sq. ft.
Concrete	660,000 cu. yd.
Structural steel.....	9,500 tons
Reinforcing steel.....	6,400 tons
Hydraulic machinery.....	6,500 tons

A maximum working force of 5300 men was employed on the project.

The design and construction of the dam and power station, including installation of hydraulic machinery and 13,800-volt electrical equipment, the relocation of the tracks of the Columbia and Port Deposit Railroad, and the design and construction of the 220-kv. switching station on roof of generator room and the transmission lines, were awarded to outside contractors. Acquisition of all lands required by the project and all negotiations with Federal, State, and County Commissions were conducted by the Power Companies direct. All matters of design and construction were also under the general supervision of the Power Companies.

Discussion

For discussion of this paper see page 906.

Electrical Features of the Conowingo Generating Station and the Receiving Substations at Philadelphia

BY R. A. HENTZ¹

Member, A. I. E. E.

Synopsis.—The paper outlines the principal electrical features of the Conowingo development. This includes a description of the main units and their connections, and an outline of the station auxiliary supply and the 220,000-volt substation which it was necessary to build on the roof of the power plant.

A description is included of the 220,000-volt substation at Plymouth Meeting, the Philadelphia terminus of the Conowingo lines, as well as the lines of the Pennsylvania-New Jersey Interconnection. At this substation are located the 30,000-kv-a. synchronous condensers installed for stability purposes, as well as a

66-kv. installation. Three winding 220/69/13.8-kv. self-cooled transformer banks of 130,000-kv-a. rating, arranged for tapchanging under load, are installed here.

A description is also included of the Westmoreland Substation where the 66-kv. lines from Plymouth Meeting tie in with the 66-kv. "backbone" of the Philadelphia Electric System. At this substation, 30,000-kv-a. synchronous condensers for power-factor correction are located, as is also an extensive 13,200-volt installation for controlling transmission lines to various distribution substations.

* * * * *

THREE stations or substations are involved in delivering the electrical energy from the Conowingo development into Philadelphia:

- a. The Conowingo Hydroelectric Generating Station.
- b. The 220/66-kv. step-down substation at Plymouth Meeting just outside Philadelphia.
- c. The combined 66-kv. switching station and 66/13.2-kv. substation in Philadelphia (the Westmoreland Substation) where tie in with the existing system of the Philadelphia Electric Company is effected.

These, together with the steam generating stations and high-voltage substations of the Philadelphia Electric System are shown in Fig. 1.

CONOWINGO GENERATING STATION

The ultimate development provides for eleven 40,000-kv-a. generators and three 220-kv. transmission lines, of which seven generators and two lines are being installed initially.

13.8-Kv. and 220-Kv. Layout. Fig. 2 is the main one-line diagram, the initial installation shown solid, the future dotted.

The 40,000-kv-a. main units generate energy at 13,800 volts and step up to 220,000 volts through 80,000-kv-a. transformers. It is planned to operate the plant as a whole in parallel on the 220-kv. bus, but to reduce the cost of transformers and 220-kv. switching equipment, two generators are tied together and to a transformer bank, thus forming an 80,000-kv-a. group. Thus ultimately, if such operation is satisfactory, there will be six such groups paralleled only on the 220-kv. side, except that the last one (generator No. 11 and transformer No. 6) will be necessarily of but 40,000-kv-a. capacity.

Should it at some future time be deemed desirable for any reason to operate in parallel on the 13.8-kv. side, then by means of additional construction the

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various buses of this voltage may be tied together, some through reactors, to form either a four-section ring bus or a three-section straight bus. The reactors may be cut out by means of a disconnecting switch (operated only when no current is flowing through the reactor). Initially the No. 3-No. 4 and the No. 5-No. 6 sections are tied together by an oil circuit breaker, thus providing greater flexibility of operation between these four generators. It will be noted that generators Nos. 3, 6, and 9 and transformer banks Nos. 2, 3, and 5 may be double-bussed in the future should the 13.8-kv.

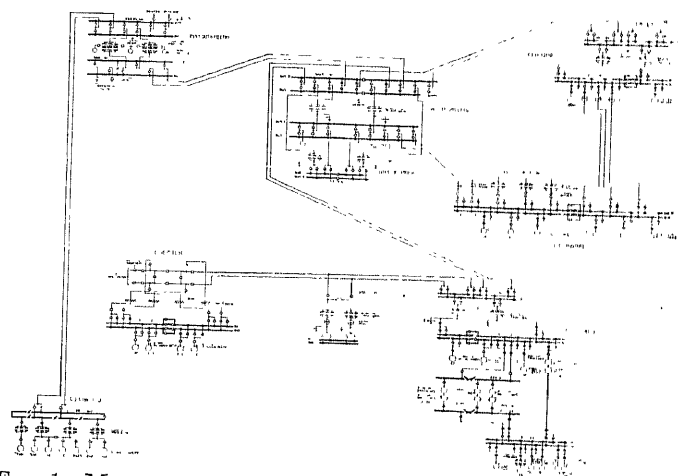


FIG. 1—MAJOR CONNECTIONS OF THE PHILADELPHIA ELECTRIC CO. SYSTEM

ring be formed. This is to permit testing a 220-kv. line from a generator (about one-half the capacity of which is required for such test) with the least interference to the maximum output over the remaining line or lines.

There will be two feeders, each connected to separate sections of the 13,800-volt bus to supply a transformer bank used for station service, and provision is made for two other feeders for the future supply to communities in the vicinity.

Two plans for the 220-kv. structure were considered;

one a complete double bus layout which due to the characteristics of the site would have to have been located on the west shore some distance from the power house with consequent high cost and operating inconveniences due to distance from the operating room; the other the most flexibly operated bus that could be

breakers for the lines, and immunity from protracted shut-down due to failure of a part of the bus. On account of their more frequent tripping and the speed with which lines can be restored to service, as well as the greater capacity involved, reserve breakers for the lines were considered essential, whereas one oil

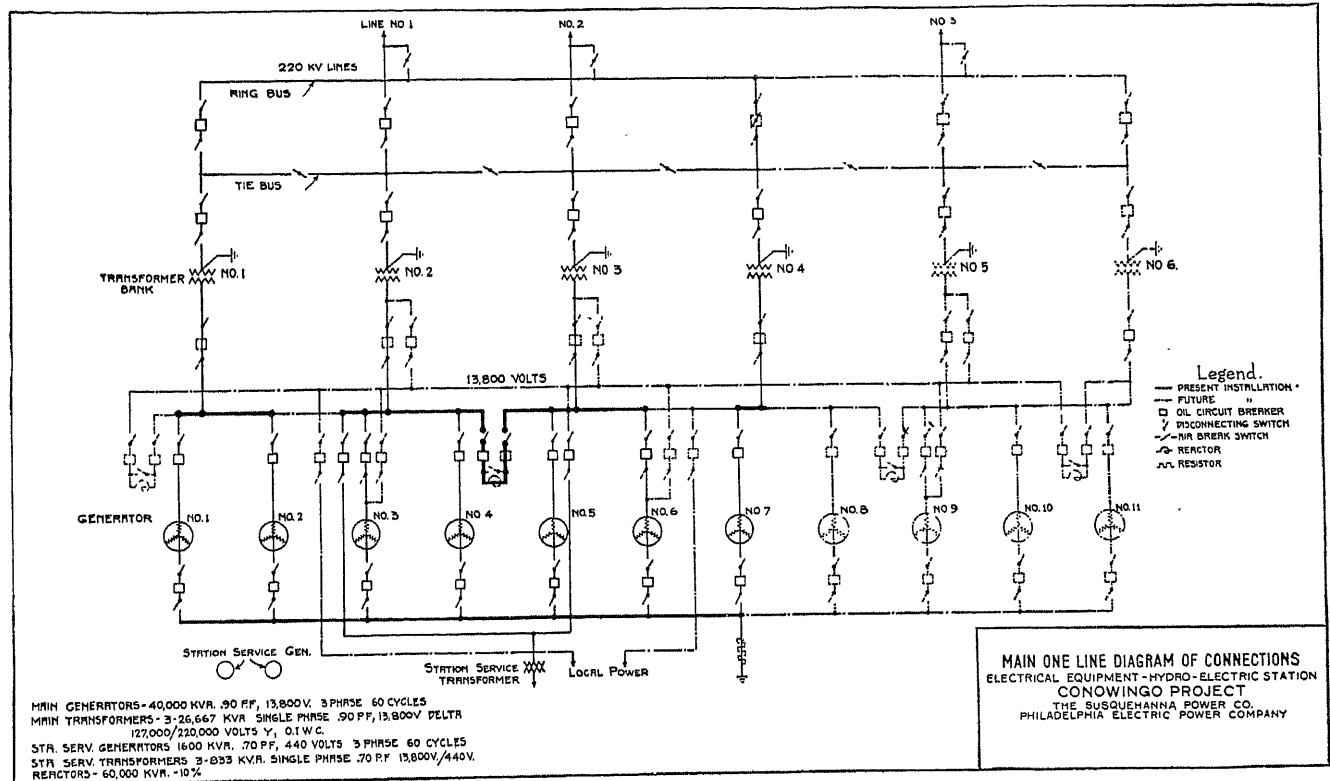


FIG. 2—SINGLE-LINE DIAGRAM OF THE CONOWINGO POWER STATION

located on the roof of the power house, which location would be considerably cheaper and more conveniently operated than the first. This latter was decided upon, as it was possible to develop quite a flexible layout

circuit breaker was felt to be sufficient for a transformer bank.

The reserve line oil circuit breakers are located

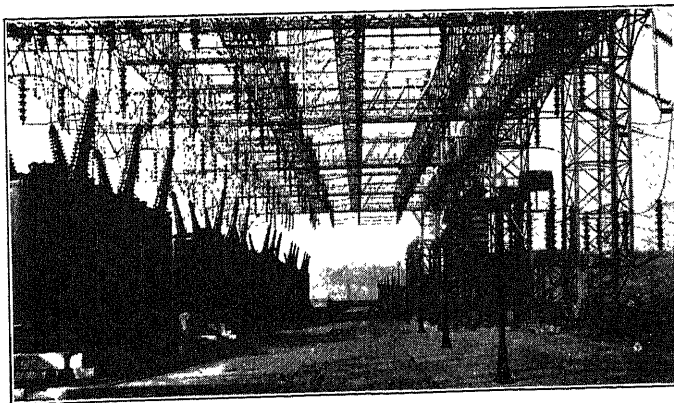


FIG. 3—GENERAL VIEW OF THE 220,000-VOLT INSTALLATION ON THE ROOF

To the left, 2,500,000-kv-a. oil circuit breakers; to the right, 220-kv. lightning arresters.

within the space limitations and to incorporate two features, inherent in a double bus layout, that were felt to be essential. These were reserve oil circuit

breakers for the lines, and immunity from protracted shut-down due to failure of a part of the bus. They are provided

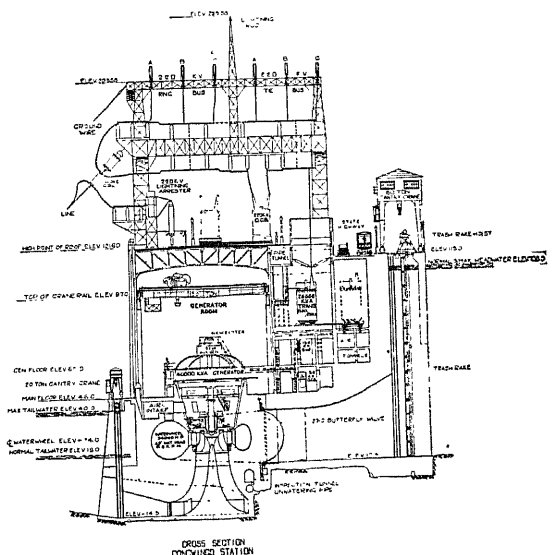


FIG. 4—CONOWINGO POWER STATION CROSS-SECTION

with the same relay equipment as the regular line breakers, and by opening the latter and closing the ring-bus-line air-break switch, (which is motor-operated and interlocked in the same manner as the bus sectionalizing switches), the reserve breaker is electrically substituted for the regular one. Fig. 3 is a general view of the 220-kv. oil circuit breakers.

Quick isolation of a defective section is provided for by several motor-operated bus sectionalizing air-break switches. These are arranged so that they cannot open or close under load by an interlock consisting of a plug, the insertion of which in a certain receptacle will close the operating circuit of the air-break switch motor, provided the several associated air- or oil-break switches are in such a position (open or closed) that no current will be interrupted by the particular air-break switch to be operated.

The above outlines the essential features of the electrical layout. A cross-section is shown in Fig. 4.

Station Auxiliary System. Fig. 5 is a one-line dia-

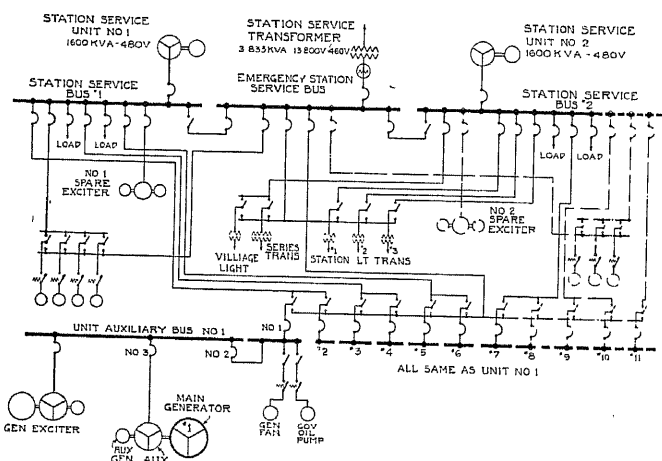


FIG. 5—440-VOLT STATION SERVICE AT CONOWINGO

gram of the 440-volt, three-phase station auxiliary system. This may be divided into two parts: first, that to supply the essential auxiliaries of each main unit (this is obtained from alternators which together with their excitors are directly connected on the shaft of the main unit); and second, that to supply the less essential auxiliaries and the general lighting of the plant. This is obtained from two 1600-kv-a. station service turbine generators (with direct-connected excitors), and a 2500-kv-a. station service transformer bank. This latter is connected as noted above to two 13,800-volt sections and is provided with an induction regulator on the 440-volt side to compensate for large voltage variations on the 13,800-volt side.

The essential auxiliaries associated with each main unit are an exciter set, a governor oil pump, and a generator ventilating fan. Of these of course the most essential is the exciter and for this reason the unit auxiliary bus is divided into two parts tied together through a circuit breaker, so that the generator fan and governor oil pump may be disconnected, allowing

the shaft-end auxiliary generator to continue driving the motor-generator set. The governor oil pumps for each pair of units are each capable of supplying the governors of both main units and both are running all the time. The generator fan is not needed when the air is being discharged into the turbine hall.

Emergency supply to all of these essential auxiliaries is obtained by feeders from the station service buses, one feeder being extended for each pair of generators. In addition there is another emergency feed common for all generators.

The general station service supply is from a single bus sectionalized into three sections which are tied together by air circuit breakers. To each section a station service turbine generator or transformer bank is connected so that the bus may be operated in one, two, or three parts as desired.

A spare motor-driven exciter for the main generators is connected to one of these sections and a second spare exciter may be added to another in the future. The miscellaneous motors throughout the plant are supplied in practically every case by two feeders, extended from different sections. It will be noted from the diagram that the main feeders are connected to the bus section supplied by the turbine generator units and the emergency feeders to that supplied by the transformer bank.

The lighting is obtained from three 200-kv-a., single-phase, 440/110-220-volt transformers. The lighting is thus divided into three independent parts, though each part may be supplied from either of two transformers by means of double-throw knife switches. In each of these three lighting groups is a number of circuits which will be thrown over automatically to one of the two control storage batteries in the event of failure of the regular a-c. supply. Two 20-kv-a. series lighting transformers are installed for lighting the highway over the dam. A bank of transformers stepping up to 2300 volts, three-phase, is used to supply service to the operating village nearby. Air circuit breakers are used throughout on the 440-volt auxiliary system.

Excitation System. As noted above, each of the main generators is excited from individual motor-generator exciter sets. These consist of a 375-hp. induction motor, a 240-kw., 250-volt main exciter, and a 10-kw., 250-volt pilot exciter operating at 1200 rev. per min. Consideration was given to having these exciters mounted on the same shaft with the main unit, but due to their capacity and the slow speed (81.8 rev. per min.) a very expensive exciter of quite large dimensions and of slow response would have resulted if indeed they could have been satisfactorily built. As high-speed excitation was essential for stability of operation, it was necessary to use motor-generator exciters.

This high-speed excitation has been described in the technical press.² The regulator is a combination of

2. "Quick Response Excitation for Alternating-Current Synchronous Machines," C. A. Powel, *Electric Journal*, April 1927, p. 157.

rheostatic and vibrating contact types, the general principle being that for sudden changes of load the contacts raise or lower the voltage very quickly and the face plate rotates to a new position after which the contacts cease vibrating. This combines the advantages of the two types, obtaining the quick response of the one and the reduced contact maintenance of the other.

Circuit breakers are installed so that excitation for each unit may be obtained either from the regular motor-generator exciter, or either of the two spare exciters. Emergency excitation for the auxiliary generators and the station service generators may be obtained from the spare exciters in the same manner.

Main Generators. The main generators are of unusual size, rated 40,000 kv-a., 36,000 kw., 90 per cent power factor, 13,800 volts, three-phase, 60 cycles. Though there are others of larger kw. capacity, yet on account of their slow speed, these are physically the largest ever built. They are provided with 88-poles and operate at 81.8 rev. per min. Mounted on the same shaft and

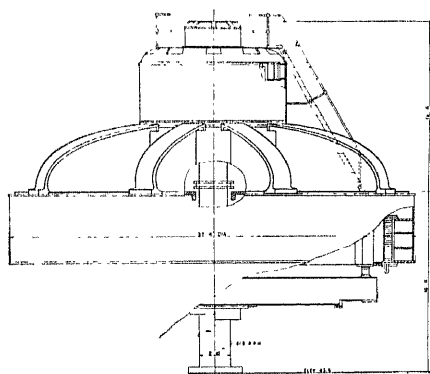


FIG. 6—40,000 KV-A. GENERATOR

above the thrust bearing is a 715-kv-a., 500-kw., 70 per cent power factor, 440-volt, three-phase, 60-cycle generator and its 41-kw. 250-volt exciter. Four of the units are provided with spring type thrust bearings and the other three, with Kingsbury thrust bearings. The designs of the two manufacturers who built the generators have been so worked out that the units have the same general dimensions, which adds greatly to the appearance of the generator room. The neutrals of both the main and auxiliary generators are brought out for differential relay protection and in the case of the main generators are then grounded through a 4-ohm resistor which is common to all of the units, even though groups of these generators are separated from one another on the 13,800 volt side. The neutrals of the auxiliary generators are ungrounded. Fifteen temperature resistors are provided in the main machines and operate recording temperature indicators. The generators are roughly 38-ft. in diameter, 32-ft. high, and weigh, together with the thrust bearing, auxiliary unit and its exciter, well over 500 tons on the average.

See Fig. 6. The weight on the thrust bearing including water thrust is 1,200,000 lb.

Main Transformer Banks. Each main transformer bank is of 80,000-kv-a. capacity, consisting of three 26,667-kv-a. units, Y-connected on the 220-kv. side, with solidly and permanently grounded neutrals, and delta on the 13.8-kv. side. Four of these banks are being installed initially together with a spare single-phase unit, making thirteen transformers in all. They are provided with one seven and one-half per cent tap in the high-tension winding and are insulated for 187 kv.

The units are water-cooled and normally receive their water supply directly from the lake formed by the dam, the water flowing through the cooling coils by gravity. When reduced pond level makes it necessary, motor driven pumps supply the cooling water.

The transformer may be run on its own wheels on to a transfer car which carries it to the west end of the plant, where a crane lowers it to the same level as the generator room into which it is run over the yard tracks.

Oil Circuit Breakers. The oil circuit breakers for 220,000-volt service are rated 187-kv., 1000-ampere, 2,500,000 kv-a. rupturing capacity. Potential networks are attached to the condenser bushings which will supply potential for synchronizing and the operation of impedance relays and instruments. These breakers in their permanent position rest on two I-beams. Their removal is accomplished in the following manner: Four jacks raise a single pole of the breaker a sufficient distance to allow a small car to be slipped under it; it is then lowered until it rests on this car in which position it just clears the I-beams. This small car with the breaker is then moved on to a larger car which is then moved to the west end of the station, where the smaller car carries the breaker under a crane which lifts it down into a bay similar to those in which the main transformers are located. From here it is taken into the plant in the same manner as the transformers.

The 13.8-kv. breakers are rated 15 kv., but are insulated for 25 kv. as are also all the insulators and current transformers. The generators and light and power breakers are of 2000 ampere capacity, the bus tie of 4000 ampere capacity. They are motor-operated, and have a rupturing capacity of 1,500,000 kv-a. The section of the station in which they are located is divided into a number of smokeproof compartments so that fire and the resulting soot will be confined to a comparatively small area.

Relays. The main generators have percentage differential relays P Q Y-28, which take care of phase-to-ground and phase-to-phase faults. No provision is made for short circuits between two sections of the same winding or between turns of each section. Over-voltage C V and mechanical overspeed relays with their contacts in parallel protect against excessive frequency and voltage that may occur upon sudden loss of load.

The unit auxiliary and station service generators

have single winding differential relays PQ and in addition the station service ones have overload COA protection.

The main transformers are equipped with two-winding differential relays $PQ-21$ and low energy ground relays CO on the low-voltage side. In addition overload relays COA provide protection against a 220-kv. bus failure between phases and act as back-up relays for the phase-to-phase relays on the 220-kv. lines.

The station service transformer bank is protected by differential $PQ-21$ and overload COA relays. Since the two 13.8-kv. sections which supply this bank would be left together if both the two breakers that control it were left closed at the same time, a long time auxiliary relay operates an alarm, thus warning the operator of this condition.

The 13.8-kv. bus sections are protected by differential $PQY-28$ and low energy ground CO relays. The two bus sections which may be tied together require a slightly amplified scheme over that required for the two that are entirely isolated.

The 220-kv. line breakers and the 220-kv. bus tie breaker (which as pointed out above may be substituted electrically for them) are each provided with:

a. Three low setting directional impedance CZ relays to provide phase-to-phase protection. Due to the fact that the maximum line current is so great and the range of connected generating capacity so large, it is possible to have phase faults with minimum generating capacity involving less than half maximum full load current. In order to properly clear under minimum generating capacity conditions and to prevent the maximum full load current from tripping the lines

b. Three instantaneous undervoltage SV relays.

c. Three instantaneous over-current SC relays are provided whose contacts are in parallel. The operation of either of these in turn operates

d. One auxiliary MC relay whose contacts normally short circuit the current coils of the impedance relays *a*. In case of fault occurring with minimum generating capacity, the voltage relay *b* operates allowing the impedance relay *a* to function; in case of fault occurring with maximum generating capacity the current relay *c* operates allowing the impedance relay *a* to function. Thus, heavy load currents will not cause relay operation unless of such high value as to operate relay *c* which is set well above maximum full load.

Entirely separate from the relays described above are those installed for phase-to-ground protection. These are

e. One inverse time directional CWC relay, the upper pole winding of which is connected in the residual circuit of the 220-kv. line current transformers while the lower pole winding is connected in series with the lower pole windings of other similar relays to a current transformer in the 220-kv. station ground. While this relay is entirely selective, there is also installed for the more rapid disconnection of heavy current faults

f. One plunger type instantaneous over-current SC relay connected in the residual circuit of the line-current transformers. This relay is made directional by

g. One instantaneous directional CWC relay whose contacts are in series with *f*.

There is no back-up phase-to-phase protection to the 220-kv. lines, unless the overload relays on the transformers noted above were so considered, which of course clear the supply to the 220-kv. bus. However, it is expected that phase-to-phase faults will be extremely rare. Phase-to-ground back-up protection is provided by the use of

h. One low energy ground CO relay set higher than the main relay and connected in the residual of a second set of line-current transformers (on the other bushings of the oil circuit breakers) used for instruments. Its functioning operates a second trip coil. Thus this back-up relay comes into play should the regular trip coil fail. Also it operates first on faults involving small currents.

It is to be noted that the transformer overload relays are set selectively against the line impedance relays and transformer ground relay selectively against the line ground relays.

Miscellaneous. The 220-kv. structure is unique in that it contains the first installation of 220,000-volt lightning arresters ever made. They are of the oxide film type and consist of 666 disks per leg.

Communication with the Philadelphia load dispatcher is provided by two direct telephone lines, and in addition there are lines extending to the local (Darlington) exchange. Experiments are in progress using short wavelength space radio.

Fire protection is provided by water lines, carbon tetrachloride extinguishers, and a portable Foamite generator. In addition there are two stationary Foamite generators which can be connected to a system of piping for fighting fires in the main step-up transformer banks. Ordinarily this header is disconnected from the piping in the transformer bays but can be quickly connected by means of flexible hose. Water will be used to fight generator fires, easily connected links of hose being used to make the necessary connections.

The operating room is located at about the middle of the ultimate station and is provided with a pipe room beneath. Special consideration was given to lighting (both day and night) in order to avoid glare on the instruments. A skylight with a diffusing sash beneath is used.

Installed in the operating room are three semicircular switchboards arranged one behind the other. The first is a bench board, on which are mounted control switches and indicating lamps for the control of main and direct-connected auxiliary generators, step-up transformers, and 220-kv. oil circuit breakers and air-break switches. Back of the bench board is an instrument board on which are mounted the ammeters,

voltmeters, wattmeters, reactive kv-a. indicators, etc., for the main circuits. Careful study was given to the location of equipment on the bench board and instrument board in order to facilitate accurate and easy operation. Back to back with the instrument board is a relay board on which are mounted the main protective relays. Around the rear and side walls of the room are located other boards for the control of the house service generators and transformers and for the voltage regulating equipment on the main and auxiliary generators.

250-volt control and emergency lighting is supplied from two 632-ampere hr. storage batteries and three 15-kw. motor-generator sets.

In line with the company's standard practise, telephone drop signals are used to indicate any occurrence that should be brought to the operator's attention.

Oil handling is accomplished by means of two 500-gal. per min. pumps located in the basement and five 12,000-gallon tanks located underground just outside the plant, together with an extensive system of piping. This consists of supply and discharge lines extended

the 220-kv. substation with the step-down transformers, second, the 66-kv. substation, and third, the building housing the synchronous condensers and operating room. Figs. 8 and 9 show the plan and cross-section of it and Fig. 10 gives an artist's conception of how the

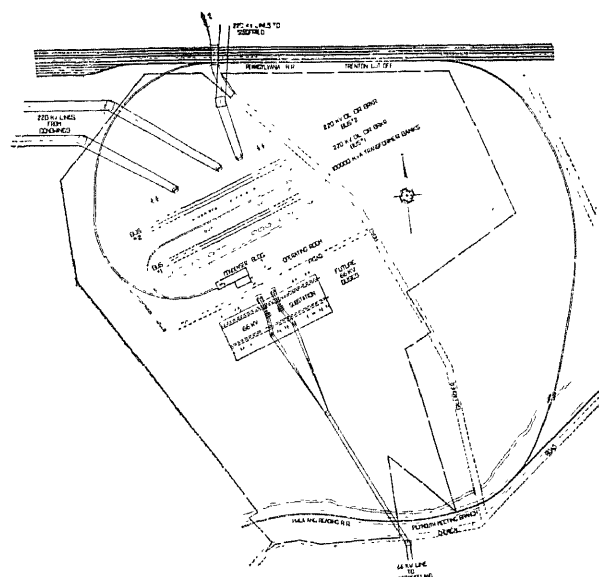


FIG. 8—PLOT PLAN OF THE PLYMOUTH MEETING SUBSTATION

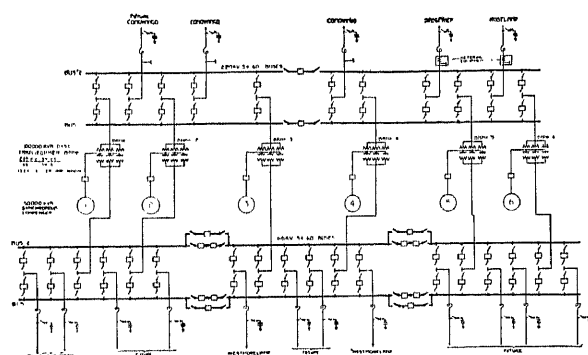


FIG. 7—SINGLE LINE DIAGRAM OF PLYMOUTH MEETING SUBSTATION

directly to the transformers and 220-kv. breakers, and conveniently near the 13.8-kv. breakers.

PLYMOUTH MEETING SUBSTATION

The location of this substation about ten mi. northwest of the Westmoreland Substation was determined not only by the fact that it would be the terminus of the 220-kv. lines from Conowingo, but also for those of the interconnection with the Pennsylvania Power & Light and Public Service Electric & Gas Companies. The particular site chosen was directly alongside a heavy freight line (the Trenton Cut-Off) of the Pennsylvania Railroad, as this provided the necessary facilities for handling the very heavy apparatus involved in a substation of this character.

The function of the station is to step-down the energy received over the above 220-kv. lines to 66 kv., the existing high capacity transmission voltage of the Philadelphia Electric System, and to provide for synchronous condensers used mainly for stability purposes. Fig. 7 is a single-line diagram of this substation which may be considered in three parts, first,

completed substation will look. The area of land purchased is 40 acres.

The 220-kv. installation consists of two sectionalized buses, (Fig. 11) each line and transformer bank selecting either bus through oil circuit breakers. Provision is ultimately for seven lines and six transformer banks, of which three lines (two from Conowingo and one to the Siegfried Substation of the Pennsylvania Power & Light Company) and two 130,000-kv-a. transformer

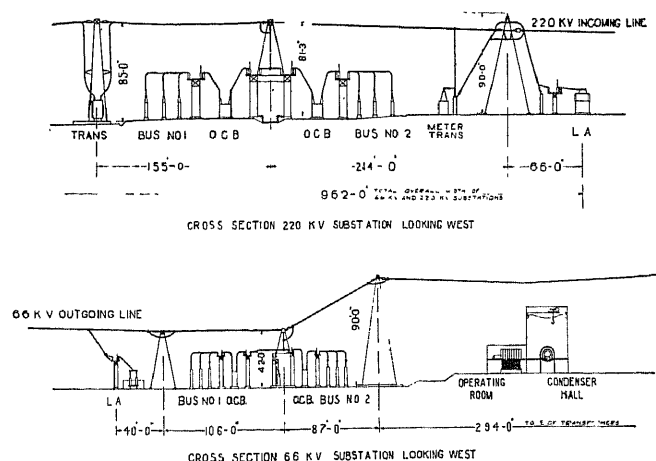


FIG. 9—PLYMOUTH MEETING SUBSTATION CROSS-SECTION

banks are being installed at this time. The oil circuit breakers are rated 1000-amperes, 187-kv., 2,500,000-kv-a. rupturing capacity. Each of the two Conowingo lines is provided with three 132-kv. potential transformers (the phase to neutral voltage of the 220-kv.

system being 127 kv.) These are used for impedance relays as well as instruments. The Siegfried line is provided with three combined current and potential transformer metering units, the potential elements of which are also used for relays and instruments. Each line is provided with a 220,000-volt auto-valve lightning arrester.

Step-down Transformer Banks. The initial installation consists of seven 43,333-kv-a. single-phase transformers forming two 130,000 kv-a. banks with a spare

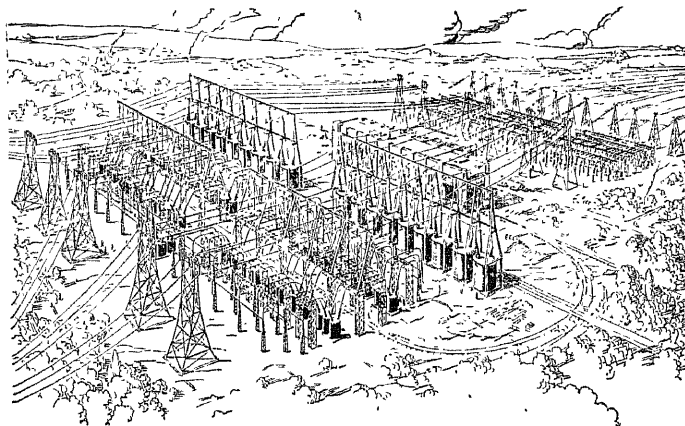


FIG. 10—PERSPECTIVE SKETCH—PLYMOUTH MEETING SUB-STATION

condensers. This tertiary is provided with a $33\frac{1}{3}$ per cent tap for starting synchronous condensers. Transformers are equipped with inertia equipment and weigh with oil 185 tons each. The tap changing under load has a voltage range of 15 per cent and in addition two five per cent taps are provided on the 220-kv. side.

Handling the heavy oil circuit breakers and transformers as well as the synchronous condensers was taken care of by a simple system of tracks shown on Fig. 8. A siding from the Pennsylvania Railroad extends in a wide sweep directly into the west end of the condenser building. At this point there is an assembly space large enough to hold a freight car and at the same time the complete transformer as is indicated in Fig. 13. In order to avoid excessive height for lifting the core of the transformer into its tank, a pit is provided in which the tank may be set and the core lowered into it. The transformer with the core inside is then raised to the floor level and its wheels put on the tracks which extend out into the switch-yard. The 125-ton crane which is ample to lift the transformer with its core and oil, is also of ample capacity to lift the 30,000-kv-a. synchronous condensers. After the transformer has been completely assembled it is moved out of the building on its own wheels onto a transformer truck which is run to a point opposite the permanent location of the transformer, when the

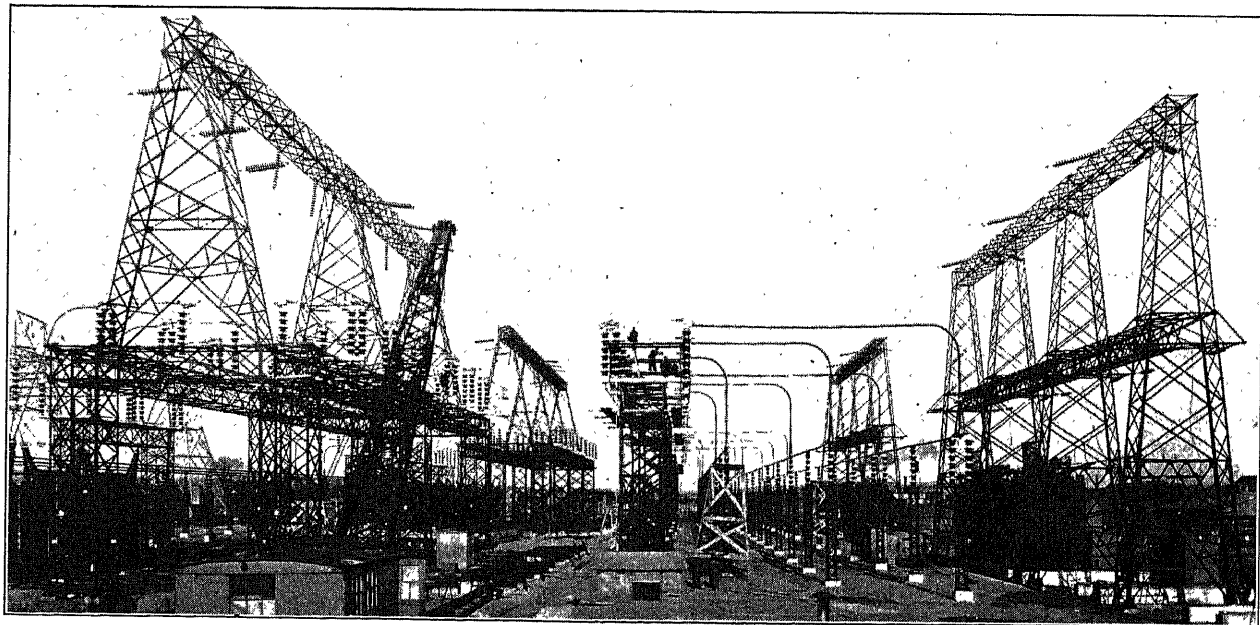


FIG. 11—GENERAL VIEW OF THE 220-Kv. YARD DURING CONSTRUCTION
130,000-kv-a. transformer banks to the right, oil circuit breakers to the left.

unit (Fig. 12). These transformers were originally rated at 33,333 kv-a. but will be increased in capacity by the application of air blown against the radiators. They have three windings: 220,000-volt, Y, 69,000-volt, Y and 13,300-volt, delta. The 13,300-volt tertiary serves the triple purpose of providing a closed delta for tap changing under load and for driving synchronous

transformer is again moved on its own wheels into position. Numerous eyes are provided in the concrete in such a manner that hauling the transfer truck is readily accomplished by means of block and fall, and a small gasoline motor.

Switching off from the railroad track that leads into the condenser building is a track which extends through

the middle of the 220-kv. structure, which is used for handling the oil circuit breakers. Each single-pole element may be assembled in the condenser building and placed on top of a transfer truck; this in turn is placed on a second transfer truck. The breaker is then moved out to a position opposite its permanent location when the upper truck is rolled off the lower one until the oil breaker is in position. By means of jacks the breaker is lifted free from the truck and finally down on its I-beam foundations in a manner similar to that used at Conowingo. A track is also provided which will permit getting the potential transformers and metering units close to their location from which point they are skidded the short distance into position. It has been found on the initial installation alone the saving in handling heavy apparatus paid for the tracks and transfer cars.

66-Kv. Substation. The 66,000-volt substation is of practically the same design as at Westmoreland and the description of this latter given below will suffice.

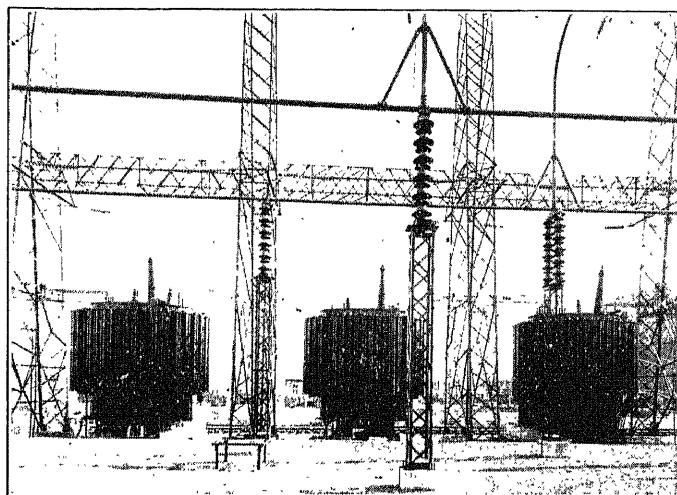


FIG. 12—130,000-KV-A., 220/69/13.3-KV. SELF-COOLED TRANSFORMER BANK

The only exception is that all of the lines at Plymouth Meeting are overhead, whereas most of those at Westmoreland are underground. Provision is made, however, for taking any of the lines from Plymouth Meeting out underground, though it is doubtful if this would ever be done. Initially this 66-kv. substation consists of sections for the two transformer banks, the two lines to Westmoreland and two lines to the Barbadoes Island Generating Station of the Philadelphia Suburban-Counties Gas & Electric Company at Norristown. Lightning arresters are installed on all four lines.

Synchronous Condensers. In addition to providing facilities for assembling transformers, oil circuit breakers, metering units, and potential transformers as described above, the condenser building is arranged to ultimately house six 30,000-kv-a. synchronous condensers. The building initially, however, is erected for three and three are being installed at this time.

These condensers operate at 600 rev. per min. and are provided with a scheme which gives extra high-speed excitation. This has been described in the technical press.³ Each condenser is provided with a main 165-kw., 250-volt, six-pole, compound-wound exciter and a 40-kw., 250-volt, six-pole, compound-wound pilot exciter, one mounted on each end of the same shaft.

The condensers at this location are to be used pri-

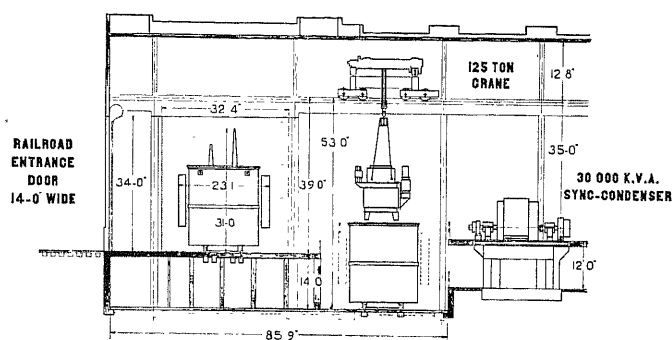


FIG. 13—PLYMOUTH MEETING SUBSTATION
Method of handling 43,333-kv-a., 220-kv. transformers

marily for stability purposes and will normally be carrying a light load. However, upon failure of one of the two Conowingo lines they will instantly supply the additional reactive kv-a. necessitated by one line operation as compared with two lines, and by holding up the voltage will materially stabilize the operation of the combined systems. This is accomplished by the regulator short-circuiting a resistance in the main exciter field causing the armature voltage to rise at a rate of 6000-7000 volts per sec. and applying a "ceiling"

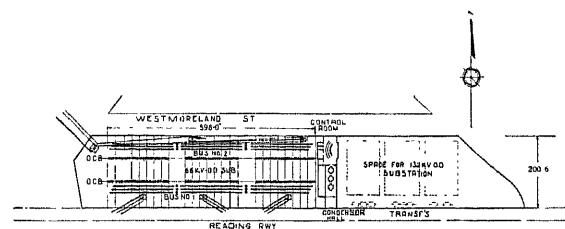


FIG. 14—WESTINGHOUSE SUBSTATION PLAN

voltage of about 1000 on the nominal 250-volt fields of the condenser. It is planned to operate them normally at about 10,000 kv-a., though this may be varied in the light of operating experience. Under certain conditions they will be able to deliver about 55,000 kv-a. each and this increase of 45,000 kv-a. will be brought about in half a second.

The condenser starting and running oil circuit breakers are located outdoors between the transformers and the condenser building and from these are tapped

3. "Super Excitation," D. M. Jones, *G. E. Review*, Dec. 1927, p. 580. "Super-Excited Condensers," O. A. Gustafson, *Elec. World*, Feb. 18, 1928, p. 349.

off two banks of transformers which step-down to a 110-220-volt system for light and power supply.

In an extension of the condenser building is located the operating room with pipe room beneath. The section now built houses all of the 220-kv. switchboards and those controlling the synchronous condensers. Ultimately when the 66-kv. substation is further developed the operating room will be double in size to house the additional switchboards. At present the

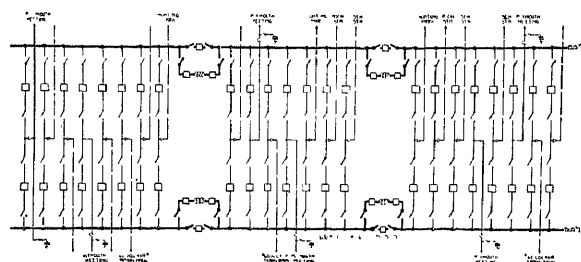


FIG. 15—SINGLE-LINE DIAGRAM OF WESTMORELAND SUBSTATION

few panels required for 66-kv. control are located at one end of the present room. Two storage batteries and two motor-generator sets are used for supplying 250-volt control and emergency lighting.

To handle the large quantity of oil involved in this substation a separate building located a little distance from the main building and built partially under ground has been erected. In this house are located centrifuges, blotter press, oil pumps, and the system of valves and manifolds which will facilitate the rapid handling of oil. Five 12,000-gal. oil tanks mounted above ground are installed near this oil house and are used: one for clean circuit breaker oil, two for clean transformer oil, and two for dirty transformer or circuit breaker oil. Permanent supply and discharge pipes are extended to the 220-kv. circuit breakers and the transformers and to convenient points near the 66-kv. circuit breakers and 220-kv. metering units and potential transformers.

Relays. The relays for the 220 kv.-lines are the same as those used at Conowingo described above.

The 130,000-kv.-a., three-winding transformer banks are provided with:

a. Three overload *CO* relays connected to current transformers located in the 220-kv. bushings. These will protect against phase-to-phase faults on 220-kv. bus, all faults on 66-kv. bus, and will act as back-ups to the 220-kv. phase-to-phase line relays.

b. Three special percentage differential *PQY 28* relays with associated balancing current transformers. The large range of the ratio adjustment possible with these banks makes the use of a percentage differential relay necessary. The balancing current transformers combine the secondary currents from the 69- and 13.3-kv. windings and balance them through the relay against the secondary current from the 220 kv. side. They also serve to isolate electrically the current transformer circuits of the three windings, two of which are

connected delta and the third star, and therefore, permit the use of standard grounding arrangement for the individual sets of current transformers. Due to the fact that there is no restraining action in the relay for transfer of power between the 69- and 13.3-kv. windings, it is necessary to use a special type of *PQY 28* relay which is sufficiently insensitive to remain inoperative under the maximum possible case of such a power transfer, and also one which is sufficiently insensitive to prevent its operation on the initial rush of charging current when the bank is energized.

The 30,000-kv.-a. synchronous condensers are provided with single winding *PQ* differentially connected relays.

The 66-kv. lines are equipped with duplex directional impedance *CZ* relays.

The station service transformer bank is protected by low energy overload *CO* relays.

WESTMORELAND SUBSTATION

The Westmoreland Substation ties Conowingo and Interconnection power into the Philadelphia Electric System. It consists of three parts, the 66-kv. substation, the 13.2-kv. substation, and combined condenser building and operating room between them. This is shown in Fig. 14.

Figs. 15 and 16 give the single-line diagram and cross-section of the 66-kv. end of the substation. The 13.2-kv. design has not been fully developed, but it will be of the group-phase, outdoor type of construction. It will be noted that the 66 kv. section consists of double bus construction, each sectionalized at two points and provided for the future installation of reactors at these points. To each of the three sections themselves, two 100,000-kv.-a. overhead lines from Plymouth Meeting will be connected or an ultimate of six, and in addition there is provision for a total of thirteen 50,000-kv.-a. underground lines and four 80,000-kv.-a. transformer

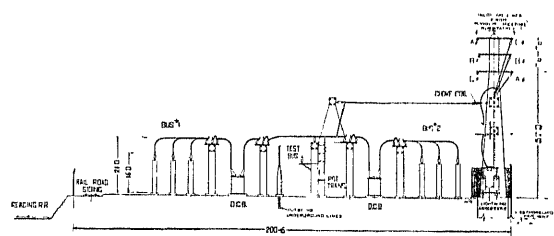


FIG. 16—CROSS-SECTION OF WESTMORELAND STATION

banks, stepping down to 13,200 volts. The initial installation will consist of two lines from Plymouth Meeting, two lines to the Richmond Generating Station and two lines to the Schuylkill Generating Station, as well as two lines extending to some small (18,750 kv.-a.) transformer banks at a nearby distribution substation, and two 80,000-kv.-a. transformer banks. The oil circuit breakers are rated 800 and 1200 amperes (the latter on the Plymouth Meeting lines), 73 kv., 2,000,000

kv-a. rupturing capacity. Lightning arresters are installed on the Plymouth Meeting lines. The relay protection consists of directional impedance *C Z* relays on all lines both overhead and underground, and differential *P Q-21* with back-up overload *C O* relays on transformer banks.

The condenser building is laid out to house ultimately three 30,000-kv-a. synchronous condensers. They will be connected to the 13,200-volt bus bars and started by means of auto transformers. Two are being installed initially, operated at 720 rev. per min. It was felt that the speed of excitation on these units need not be quite as fast as those installed at Plymouth Meeting. However, fairly high speed is desired and this is provided.

While the weights to be handled at this substation are not as great as at Plymouth Meeting, nevertheless it was felt advisable to select a piece of land adjacent to a railroad and the present site with a siding from the Reading Railroad was decided upon. The siding extends along one side of the 66-kv. substation, through the end of the condenser building, on into the 13.2-kv. substation. A 100-ton crane in the condenser building will be used not only for assembling and repairing the synchronous condensers but also the transformers and other 66-kv. and 13.2-kv. equipment, which equipment

can readily be brought into the condenser room by means of the above railroad siding and a transfer car.

Both the 66-kv. and 13.2-kv. sections as well as the condensers are controlled from one operating room which is part of the same building as the condenser room. This operating room is provided with a pipe room beneath. Adjacent and also part of the same building is an extension in which will be provision for 300,000-volt kenotron test set, offices, battery rooms, etc. A 15-kv. test set consisting of a transformer with ratio changing under load will be installed outdoors.

The 250-volt emergency lighting and control system consists of two 152-ampere-hour storage batteries and two 9-kw. motor-generator sets.

An oil handling system consisting of pumps and filters (both centrifuge and blotter presses) is provided, together with two 4500-gal. tanks located above ground, one for clean and one for dirty 66-kv. circuit breaker oil. Other tanks will be provided for the transformer banks. Supply and discharge pipes are extended conveniently to the 66-kv. breakers and directly to the transformers.

Discussion

For discussion of this paper see page 906.

220-Kv. Transmission Line for the Conowingo Development

BY P. H. CHASE¹

Member, A. I. E. E.

Synopsis.—Current from the Conowingo plant is carried fifty-eight miles to the Plymouth Meeting Substation of the Philadelphia Electric Company over two 220-kv. single-circuit steel-tower transmission lines. These lines are carried on a right-of-way which provides space for a third future line. The conductors are 795,000-cir. mil steel-reinforced aluminum. Each circuit is shielded by two 183,600-cir. mil aluminum steel-reinforced ground wires. The insulator strings consist of 14 high-strength units in suspension

position and 16 units in strain position. Conductors and ground wires are carried in a new type of slip clamp in order to decrease the unbalanced longitudinal stresses on the towers in the event of wire breakage. In general, foundations are of the earth grillage type. The tower design includes a number of novel features, among them the use of combination extensions to meet flexibly the varying topographical conditions, and the narrow waist immediately below the basket.

FOR ultimate development, the 58-mi. transmission line to Philadelphia from the Conowingo hydro-electric plant on the Susquehanna River will consist of three 220-kv. single-circuit tower lines, each circuit supported in horizontal configuration. For the initial development two of the tower lines have been constructed.

The location of the Philadelphia terminus of these lines, the Plymouth Meeting Substation, approximately 15 mi. northwest of the center of Philadelphia, was determined by a number of factors, among them the practicable transmission routes into the main 66-kv. transmission system of the Philadelphia Electric Company, and the 220-kv. transmission line routes for interconnection with Pennsylvania Power and Light Company and Public Service Electric and Gas Company of New Jersey.

The location of the right-of-way is shown in Fig. 1. That portion of the right-of-way south and west of the crossing of the Pennsylvania Railroad at Glenloch passes through a fairly level farming country. North and east of Glenloch, the right-of-way follows the general direction of the railroads through Chester Valley, a natural channel leading to the Schuylkill River between Conshohocken and Norristown; thence to Plymouth Meeting Substation. This portion of the right-of-way passes through land of the highly-developed estate type.

After determination of the general location of the right-of-way by ground reconnaissance, an airplane map was made of a strip from 1½ to 3 mi. wide, to a scale of 1000 ft. to the inch. The airplane maps were used as a basis for the final location of the line and the determination of property owners and their holdings, from which final options were prepared for negotiation with owners of record. All these steps were taken prior to any negotiations or survey activities in the field.

1. Engineer, Transmission & Distribution Division, The Philadelphia Electric Company.

Presented at the Baltimore Regional Meeting of A. I. E. E., Dist. 2, Baltimore, Md., April 17-20, 1928.

The right-of-way was secured on the principle of easements, being preferable to purchase in "fee simple."

The width of right-of-way was determined on the basis of accommodating three single-circuit tower lines, as shown in Fig. 2. The horizontal spacing between the conductors on a tower was largely determined by the clearance from the live hardware to the steel

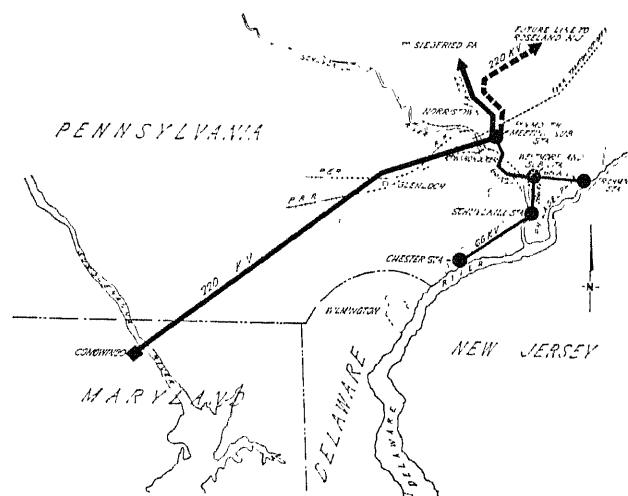


FIG. 1—ROUTE OF LINE

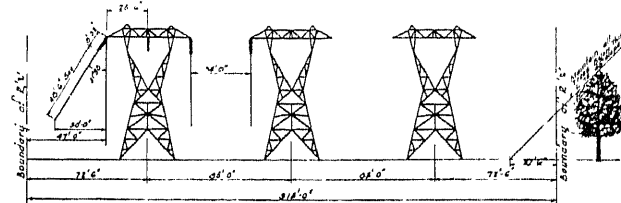


FIG. 2—CROSS-SECTION OF RIGHT OF WAY

work, with the insulator strings deflected by wind and angles. A consideration of these factors resulted in a separation between conductors of 25 ft. 6 in. on tangent towers. In determining the distance between adjacent tower lines of 85 ft., or a distance of 34 ft. between adjacent wires, consideration was given to the safety

of men working on a line adjacent to one in operation, conductor side-swing at center of span, and tower-offset.

The distance from each outside conductor to the edge of the right-of-way was determined by the amount of side-swing from wind, to which was added an additional factor for clearance.

In addition, a tree danger zone was considered to exist above a line starting from a point 45 ft. from the center line of the outside towers and extending upward and outward at an angle of 45 deg. Trees in this zone have been removed or trimmed.

BASIS OF DESIGN

The following types of towers were used on the line:

Type A—Standard suspension tower, suitable for angles up to $1\frac{1}{2}$ deg., 1100-ft. span.

Type B—Railroad crossing and angle tower, suitable for crossings, angles up to 6 deg., and tangent spans up to 2000 ft. This type, with a special top extension, was used for transpositions.

Type C—Angle tower, suitable for angles from 6 to 15 deg., and spans up to 1100 ft.

Type D—To be used for angles 15 to 60 deg., dead ends, and tangent spans up to 2500 ft.

In general, the line is designed to withstand a climatic loading of one-inch ice, but for unbalanced longitudinal load on the Type-A standard suspension tower, a tension in the conductor was taken corresponding to a load of $\frac{1}{2}$ -in. ice, it being obviously uneconomic to design for more severe conditions. Therefore, in order to minimize the stresses to which the tangent towers might be subjected under extraordinary conditions, a clamp of the releasing type was developed, to limit the maximum unbalanced longitudinal load on the tower to approximately 10,000 lb. Heavier ice loading was given consideration in the design of all types of towers for certain check conditions.

The design loads for the towers were calculated under the various assumed conditions of ice and wind for longitudinal, vertical, and transverse loading. These figures were increased by safety factors, thus giving maximum loads which the structural work of the towers was designed to withstand, using unit stresses shown in Table I.

The Type-B tower was designed to meet the requirements of General Order No. 13 of the Public Service Commission of Pennsylvania, which permitted its use for long tangent spans under non-crossing conditions when working to the allowable stresses in Table I.

The clearance diagram for the Type-A standard suspension tower is shown in Fig. 3. The clearance diagram was based on an ultimate string of 16 units and an arc control device having a probable transverse dimension of 24 in., and so located in the tower as to result in a normal clearance of 8 ft., a first accidental clearance of 6 ft. and a second accidental clearance of 5 ft. The first accidental clearance was on the basis of

an 8-lb. wind, and the second accidental clearance on a 12-lb. wind, both without ice. Due to the lack of sufficient information on the probable shape and size of an effective arc control device, it was recognized that these accidental clearances might turn out to be liberal, but on the other hand, an arc control device larger than was assumed might be installed.

TABLE I

Allowable Unit Stresses:

Limiting values of slenderness ratio:

150 for corner posts

200 for web (computed stresses)

250 for braces (no computed stress)

Compression

$38,000-165 \frac{1}{r}$ for values of $\frac{1}{r}$ up to 155,

maximum 28,000

$28,000-100 \frac{1}{r}$ for values of $\frac{1}{r}$ from 155 to 250

Tension

30,000 on net section

Bolts

22,500 shear

45,000 bearing

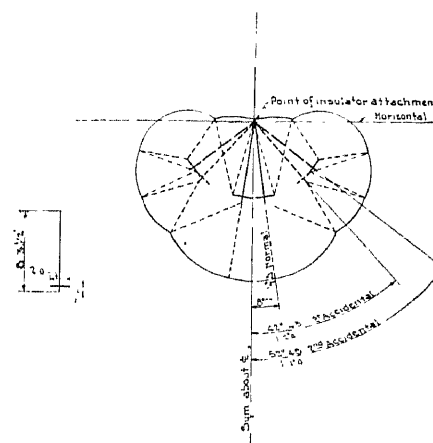


FIG. 3—CLEARANCE DIAGRAM FOR TOWERS, TYPE A

The length of span, height of tower, strength class of insulators, and characteristics of conductor must all be considered as a group, in order to determine the most economical combination and still maintain the most reliable service conditions obtainable. The size of conductor was determined by the electric loading conditions. This resulted in a conductor of 795,000-cir. mil aluminum steel-reinforced with a 40 per cent steel core, approximately $1\frac{1}{4}$ in. over-all diameter, which satisfied the corona requirements.

The conductor diameter being thus determined, and the ground clearance controlled by safety conditions, the over-all economics of tower height and span length were considered by studying various heights of towers, and for each height, increasing or decreasing the span to meet the catenary of the wire under consideration. The minimum ground clearance was 29 ft. 6 in.

TOWERS AND FOUNDATIONS

Fig. 4 shows the assembly of the Type-A suspension tower. It is designed for one three-phase 220-kv. circuit,—the conductors in a horizontal plane with a

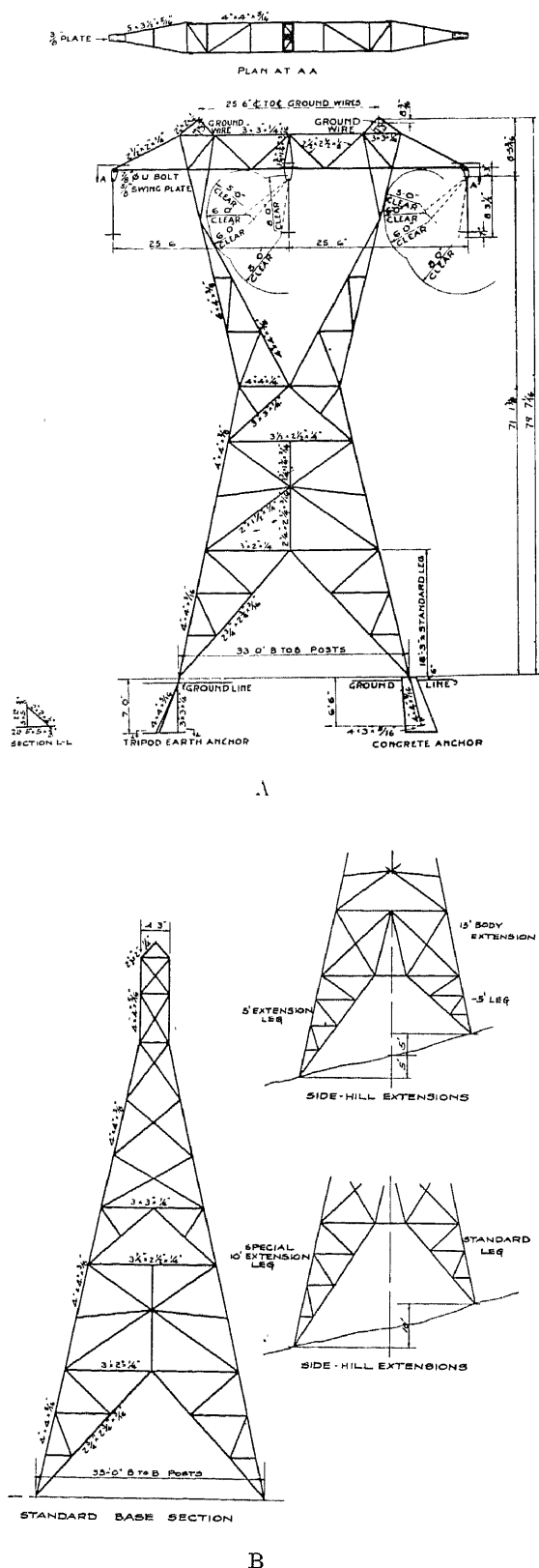


FIG. 4—TYPE-A SUSPENSION TOWER

separation of 25 ft. 6 in. Two ground wires are carried approximately 16 ft. above the plane of the conductors and midway between them. The lower section of the tower is square, so that the batter of the legs is the same in any face, resulting in a pyramidal section up to a point about 20 ft. below the conductors, where the sides flare outward to provide the necessary clearance for the middle conductor.

Particularly on account of the size of the base, which is about 35 feet square, horizontal members close to the ground line are undesirable. To avoid this, the lower section is composed of four legs, each of which is independent, and may be made of any suitable length for small extensions and for uneven ground conditions. The standard legs are about 18 ft. in height, resulting in an 80-ft. tower, but special legs, both 5 ft. shorter and 5 or 10 ft. longer, have been used. As the connections are standard, any of these legs may be used on any one of the four corners of the tower.

For extensions greater than 10 ft., an additional section is inserted in the tower above the legs. By the use of the 15- or 30-ft. body extensions, the height of the tower may be increased by 5-ft. intervals to 125 ft.

Several new features of economic value are embodied in the tower. Maintaining the square horizontal section to as great a height as possible, (to the waist line) equalizes the distribution of the torque stresses in each of the four faces of the tower below the waist. The unbalanced horizontal shear at the foundation is reduced to a minimum by fixing the legs at an angle such that if extended above the waist line they would intersect at the center of gravity of the loads. The fact that the stresses are mainly in the tower legs permits very long equal or unequal leg extensions of the same size angle.

The net result is a tower and foundation that will have the lowest weight and cost for construction for the same loading-end strength, involving horizontal arrangement of conductors.

The towers are built from galvanized structural steel shapes, the largest main member for the Type-A suspension tower being 4 by 4 by 3/8-in. angle. Connections are all field-bolted with 5/8-in. galvanized bolts. The weights of all types of towers, extensions, and anchors, are shown in Table II.

For foundations, two designs were used; for normal line construction, a structural steel tripod anchor extending 7 ft. below ground; for special construction, a concrete foundation into which is placed an extension of the main leg angle. These two anchors for the Type-A suspension tower are also shown in Fig. 4.

There are three transposition points, located at 1/6, 1/2, and 5/6 points along the line. Fig. 5 illustrates the method of construction. There is a total of 520 towers, inclusive of the Susquehanna River crossing towers, in the 57.7 mi. of line.

Particularly because the design of this tower involved a number of novel features, load tests were made in

order to check the soundness of the design assumptions. The tests verified the assumptions satisfactorily.²

TABLE II
Tower Weights

Type A Tower—

Standard top section.....	12,450 lb.
Standard "W" legs.....	560 lb.
5 ft. short "X" legs.....	470 lb.
5 ft. longer "Y" legs.....	750 lb.
10 ft. longer "Z" legs.....	900 lb.
15 ft. body extension.....	3,540 lb.
30 ft. body extension.....	7,670 lb.
Earth anchors per set.....	1,570 lb.
Concrete anchors.....	430 lb.

Type B Tower—

Standard top section.....	18,420 lb.
Standard "W" legs.....	1,070 lb.
5 ft. short "X" legs.....	880 lb.
5 ft. longer "Y" legs.....	1,340 lb.
10 ft. longer "Z" legs.....	1,610 lb.
15 ft. square extension.....	4,830 lb.
30 ft. square extension.....	11,150 lb.
45 ft. square extension.....	18,700 lb.
60 ft. square extension.....	26,700 lb.
75 ft. square extension.....	36,100 lb.
Earth anchors per set.....	2,180 lb.
Concrete anchors.....	670 lb.

Type C Tower—

Standard top section.....	20,620 lb.
Standard "W" legs.....	1,060 lb.
5 ft. short "X" legs.....	950 lb.
5 ft. longer "Y" legs.....	1,400 lb.
10 ft. longer "Z" legs.....	1,660 lb.
15 ft. square extension.....	5,210 lb.
30 ft. square extension.....	11,400 lb.
45 ft. square extension.....	18,360 lb.
Earth anchors per set.....	2,650 lb.
Concrete anchors.....	800 lb.

Type D Tower—

Standard top section.....	28,920 lb.
Standard "W" legs.....	1,990 lb.
5 ft. short "X" legs.....	1,680 lb.
5 ft. longer "Y" legs.....	2,480 lb.
10 ft. longer "Z" legs.....	3,000 lb.
20 ft. square extension.....	10,450 lb.
40 ft. square extension.....	22,300 lb.
60 ft. square extension.....	
Earth anchors per set.....	10,700 lb.
Concrete anchors.....	6,200 lb.

The size of the foundation excavations made it practicable to use a newly-designed tractor crawler crane with $\frac{1}{4}$ -yard clamshell bucket, shown in Fig. 6, which decreased the actual cost of excavation.

CONDUCTORS AND GROUND WIRE

The characteristics of the conductor and ground wire are shown in Table III.

2. See article by R. W. Wilbraham, "Load Test Check Tower Design," *Electrical World*, Nov. 12, 1927.

TABLE III
CHARACTERISTICS OF CONDUCTOR AND GROUND WIRE

	Conductor	Ground wire
Size, A C S R.....	795,000 cir. mils	183,600 cir. mils
Per cent steel core.....	39.5	73.4
	30 by 0.1628 in. Al.	18 by 0.1010 in. Al.
Stranding.....	19 by 0.0977 in. Steel	12 by 0.1214 in. Steel
Diameter.....	1.140 in.	0.707 in.
Weight per ft.....	1.234 lb.	0.6475 lb.
Ultimate strength.....	37,900 lb.	25,700 lb.
Elastic limit.....	27,300 lb.	20,100 lb.
Tension at assumed maximum load (1 in., 8 lb., 0 deg. Fahr.)	18,845 lb.	14,090 lb.
Tension at 60 deg. Fahr.....	6,180 lb.	3,880 lb.
Tension at pre-stretch.....	18,845 lb.	14,090 lb.

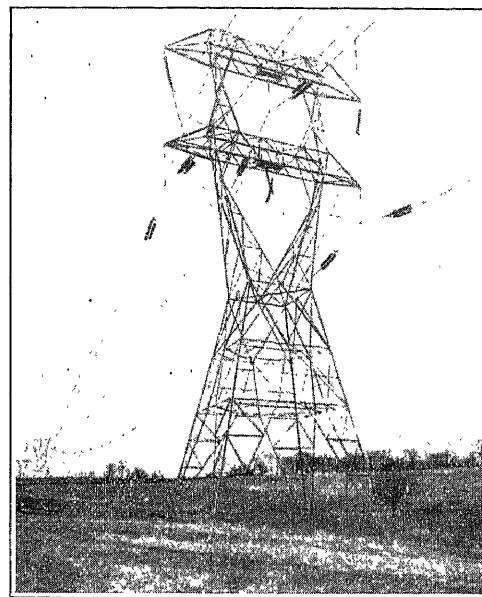


FIG. 5—TRANSPPOSITION TOWER

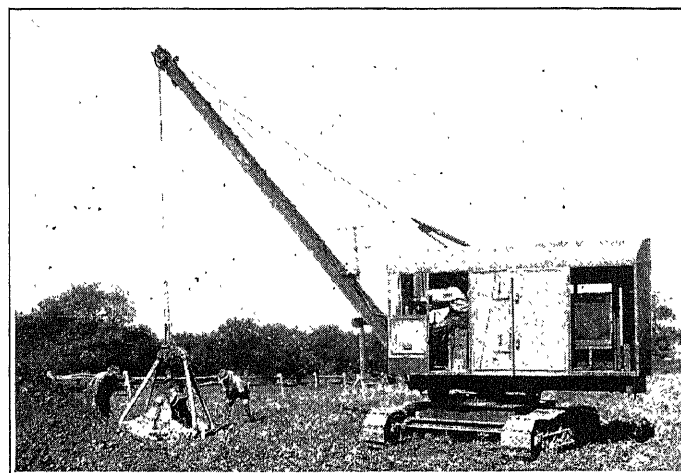
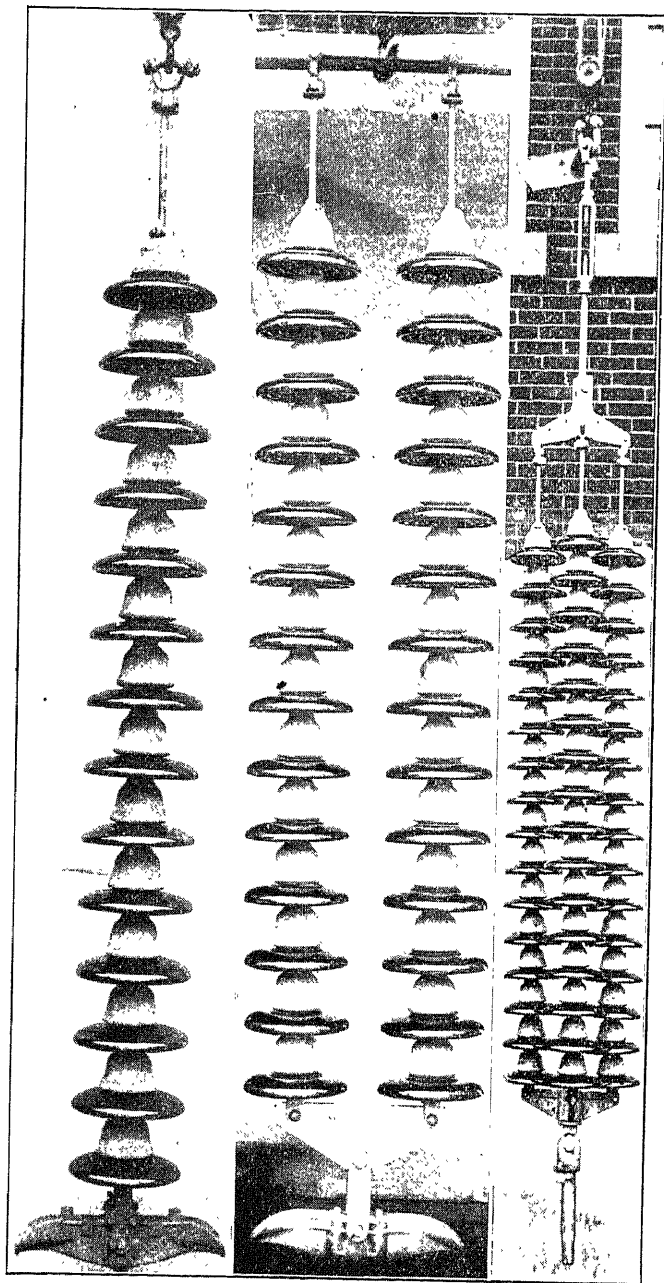


FIG. 6—CATERPILLAR TRACTOR CRANE

Considerable study was given to the characteristics of the steel-reinforced conductor, and the operating experience from all the major companies was carefully considered with special reference to eliminating troubles which have arisen in some cases from vibration of the

conductor. Considerable investigation work has been done, both by the Philadelphia Electric Company, and the Aluminum Company of America in attempting to solve this problem. Investigation work indicated that when a metal is not under an appreciable initial strain it can withstand vibration practically indefinitely, but

stretched under tension the aluminum strands first share the strain with the steel until they are stretched beyond their elastic limit, at which time they take a permanent elongation. As the strain on the cable is released, the steel core, due to its greater elasticity, begins to pick up the strain and relieve the aluminum



A B C
FIG. 7—INSULATOR STRINGS AND CLAMP

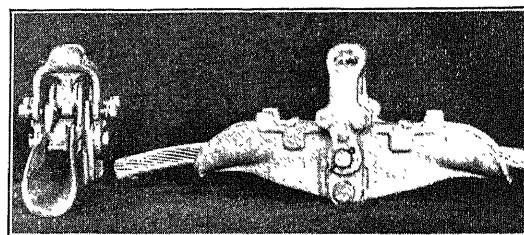


FIG. 8—RELEASE CLAMP

strands. This indicates the advisability of pre-stretching the cable. This pre-stretching secures two advantages, the first of which is indicated above in obtaining the reduction of the stress in the aluminum strands, and the second is that it establishes the modulus of elasticity of the cable, so that its characteristics, and consequently the sag, will not vary when the cable is subjected to a heavy ice and wind loading.

In a cable having a content of about 40 per cent by weight of steel, stress-strain curves show that after pre-stretching there is practically no tension in the aluminum strands under the ranges of temperature which usually exist at those times when vibration is most severe, namely, in fairly cold weather and with light winds. Experience has shown, further, that in practically every case where trouble has been experienced with broken strands, the steel content has been in the neighborhood of 25 to 30 per cent, and no strand failures with the 40 per cent content have been reported.

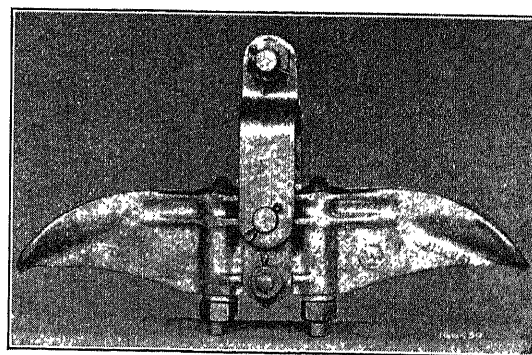


FIG. 9—NON-RELEASING CLAMP

that its ability to withstand vibration decreases as the initial strain increases. This principle also applies to the aluminum strands of a cable.

Further investigation work on the modulus of elasticity of the finished cables has shown that the modulus depends upon the maximum tension which the cable has withstood. This is due to the fact that as the cable is

In selecting the ground wire, it was concluded that it should be of the same general nature as the conductor, so that both materials would act in the same manner in unloading ice coatings; also that they should have approximately the same sag and swing characteristics. As an aluminum steel-reinforced cable was selected for

the conductor, the same type of cable was selected for the ground wire.

Consideration also was given to securing a ground wire having sufficient current-carrying capacity to meet the requirements of lightning protection, and also to distribute any currents which might flow into the tower

pension strings and 18 units for triple dead-end strings. The initial installation is with 14 units in suspension and 16 for triple-yoke strings, with a spacer link next to the tower having a length equal to two insulators, so that the conductors in every case are in the ultimate position.

The single, double, and triple string assemblies are shown in Fig. 7.

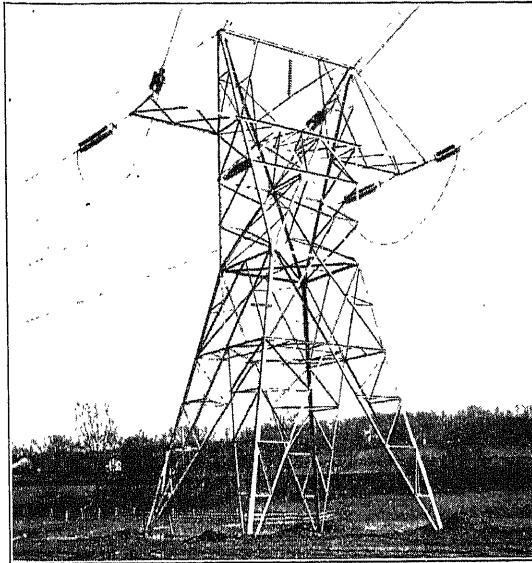


FIG. 10—DEAD-END TOWER AND JUMPER CONSTRUCTION

under the condition of an insulator flashover. It would have been possible to meet the above requirements with an all-steel galvanized cable, but a layer of aluminum strands outside the steel core has a preservative effect on the galvanizing, and consequently a cable with a steel core of approximately the same size as the

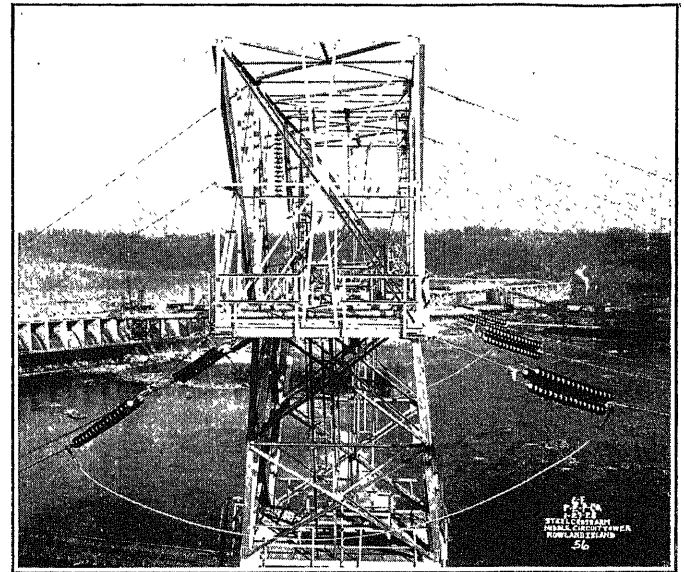


FIG. 12—SUSQUEHANNA RIVER CROSSING

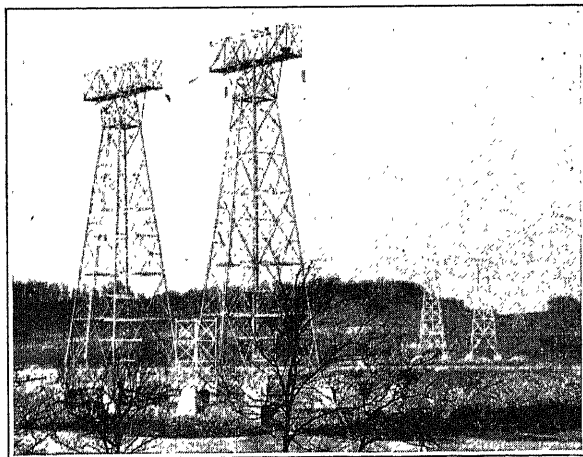


FIG. 11—SUSQUEHANNA RIVER CROSSING

conductor and carrying two layers of aluminum strand, was finally selected.

INSULATORS AND HARDWARE

The line is insulated with high-strength 10-in. disk insulators with $5\frac{3}{4}$ -in. spacing. The design provides for an ultimate of 16 units for single and double sus-

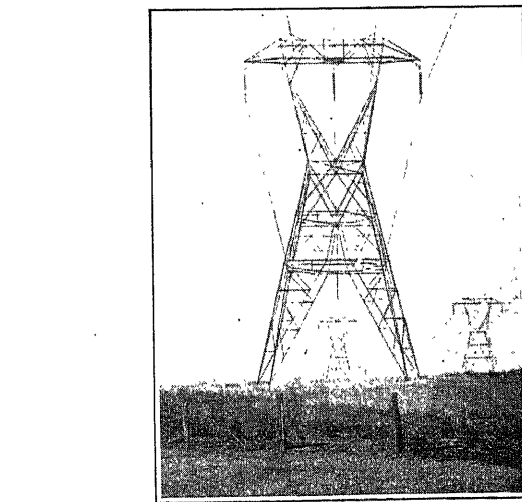


FIG. 13—TYPICAL LINE CONSTRUCTION

Except at points of special construction, the conductor and ground wire are carried in a releasing type of clamp, shown in Fig. 8. For special suspension construction, a non-releasing clamp as shown in Fig. 9 was used. Both clamps are of galvanized cast steel. In order to reduce the vibration-reflecting characteristics of the

clamp they are free to swing in a vertical plane about an axis intersecting the axis of the conductor.

The releasing clamps are so designed that an unbalanced pull which will produce a longitudinal swing of 20 deg. of the insulator string will completely release the clamping mechanism. The wire is then held only by the friction in the saddle of the clamp. By the use of these clamps the longitudinal pull from a broken wire is restricted to a small fraction of the strength of the wire and under heavily loaded conditions should not exceed 5000 lb. This results in longitudinal tower stresses considerably less than if the release clamp were not used.

On the dead-end towers, the middle conductor is carried above and through the center of the tower, as shown in Fig. 10. The great distance from outside to outside of insulator string, for the center conductor made it impossible to support the jumper with a suspension string in the center and avoid the stranded conductor sagging to such a point as to decrease the clearances below safe limits. In order to maintain an economical design of tower top, recourse was had to carrying the stranded aluminum conductor in a 3-in. aluminum pipe, 24 ft. long. To each end was attached an aluminum reducing coupling carrying a 3-ft. extension of 1½-in. aluminum pipe from the end of which the conductor dropped free into the 90-deg. compression aluminum dead-end fitting.

Provision has been made for the attachment of arc control devices. A decision has been made to install some form of arc control device in the near future.

The transmission lines leave the power house on the west bank and are carried to the east bank in two spans—1450 and 2200 ft., respectively. The intermediate towers are located on an island in the channel of the river, and act as a dead-end and single tower, greatly diminishing the stresses on the roof structure. These towers are shown in Figs. 11 and 12. They are 228 ft. high (above the foundations), weigh 113 tons each, and have a base spread of 60 ft., supported on concrete piers 20 ft. above ground, with a bridge-type walk-way interconnecting the piers.

To provide communication from the river bank to these towers at times of high water, a cable-way of 1½ tons capacity has been installed.

The towers are of structural steel, the lower two-thirds riveted for rigidity, and painted with aluminum paint. The upper third is galvanized structural steel, bolted, in order to avoid maintenance painting adjacent to live parts. On the top bridge, on the crossarm of the towers, permanent rigging-booms have been provided, in order to facilitate maintenance operations.

The author wishes to express his appreciation of the helpful assistance in the preparation of this paper which was given by Mr. R. W. Wilbraham of the Day & Zimmerman Engineering & Construction Co. and Mr. W. W. Woodruff of The Philadelphia Electric Company.

Discussion

THE CONOWINGO DEVELOPMENT

(WILSON, HENTZ, AND CHASE)

BALTIMORE, MD., APRIL 19, 1928

F. G. Baum: The interesting thing about the Conowingo power station itself is the speed at which the work was done. It would have been very interesting if the authors had added the cost of this development.

I had occasion last year to look over a hydroelectric project in a foreign country where they had \$6,000,000 to spend on the job, a much easier piece of work than this, and the job was laid out to be done in four years. I told them that they were losing two years in output and two years in interest charges.

The total result of the comparison is this, that while labor costs are about one-third of ours, when they get through building a power plant they have about as many dollars in the job as we have here. This results largely from the extra time taken to do the work.

I am very happy to see the eastern engineers finally coming to 220-kv. transmission. I believe that under that voltage we haven't any real transmission voltage, because the amount of power you can get even over a 110-kv. line is so small it is really a distributing line. We have had now, in northern California, five years' experience with 220 kv. Starting with 11-kv. lines built 30 years ago and extending up gradually to the 220-kv., the 220 was the first line we built that surpassed our expectations. Previous to that we were always more or less disappointed in our transmission results, and not only in the amount of power but in the security of service. Very often it is figured that the exposure from service interruption depends on the number of miles of exposure but what you really are interested in is the number of interruptions, say, per million kw-hr. delivered, and that certainly is going to be much less at 220 kv. than at 110 or lower voltages.

I believe that the system adopted for this transmission was the one solution which was right; that is, the decision for a *constant* voltage system brought about by synchronous condenser voltage regulation.

F. C. Hunker: The problem of the Conowingo System is largely one of insuring, in so far as possible, continuity of supply to the ultimate user. That problem, when you come to the larger power plants, located some distance from the load center, involves the additional link of transmission. As Mr. Baum has pointed out, the records on the Coast have shown very satisfactory results on the higher voltages. There has not been the same period of operation in the East, but surely, with the amount of engineering talent applied to the problem, we can expect that after some of the initial troubles are overcome satisfactory service will be secured.

In the Conowingo Development, fortunately, we had the benefit of a number of years of analytical work and field testing combined with the experience on the pioneer work of the West on longer lines. The studies indicated that a very considerable improvement in the operating results could be obtained by special characteristics in the apparatus to improve operating stability.

Those improvements in the characteristics of the apparatus have been made possible to a greater extent on some of the Coast propositions where the generating capacity and the accompanying equipment do not represent as large a percentage in the total investment. In those cases you can afford to put considerably more expense into apparatus than in the ordinary case where the generating and regulating apparatus is a smaller proportion of the total cost.

There has been theoretical discussion on load limitations of systems and the problem is becoming more generally recognized. What we need now is more operating experience with apparatus having improved characteristics and the results of the next few years will show the justification for the expense involved.

R. L. Thomas: Mr. Wilson in his paper has referred to one feature of the Conowingo development which is perhaps unique, namely the backwater or pond-level agreement with the Holtwood development of the Pennsylvania Water & Power Company. The details of this arrangement belong in the field of civil rather than of electrical engineering but a number of questions has been asked and a brief statement regarding the scheme may be of interest.

The Holtwood Development is located in Pennsylvania about 15 mi. upstream from the Conowingo Development. When the Pennsylvania Water & Power Company took over this development and completed the initial installation in 1909 and 1910, the tailrace as planned was already completed. The plant has been located at the upper end of an island, forming a natural tailrace consisting of a very irregular, deep, and narrow channel about two-thirds of a mile in length. When unwatered it looked like a gorge. No improvements had been made on it. Below this natural channel there was originally a reef which formed a rapids about half a mile long, ending in another deep pool. These deep pools are rather characteristic of the Susquehanna. Through that reef the McCall Ferry Power Company had cut a canal, but they left what amounted to a flat rock weir at an elevation of 101 1/2 ft. above mean sea level for the purpose of sealing the draft tubes of the turbines. Also their canal was designed for a flow of 20,000 cu. ft. per sec., whereas the Holtwood power house, as subsequently developed, actually discharges 30,000 sec.-ft. at full load. This increased discharge and the naturally poor hydraulic characteristics of the tailrace resulted in a maximum drop through the tailrace of about 14 ft. at full load with no water flowing over the Holtwood Dam. This represents a lot of power, and obviously it was economical to try to regain as much of it as possible.

In 1916 the company started on an ambitious excavation scheme, calling for a large amount of subaqueous rock excavation. Naturally the power house could not be shut down and on account of the swift current the work involved was expensive and difficult. It was suspended in 1917 on account of the War. About the same time studies were being made of the Conowingo project, the estimates being based on a clear-crest dam with crest at an elevation of about 100 ft. above mean sea level. Studies made at that time showed that a method of developing the loss in the Holtwood tailrace more economically than by excavation would be to superimpose steel gates or a movable dam of some kind on the Conowingo dam so as to maintain a water level there considerably higher than had been contemplated previously, and thus back water into the Holtwood tailrace and partially "drown out" the rapids there with, of course, some consequent loss in head at the Holtwood plant. In effect the proposition was to transfer a varying amount of head from one plant to the other. Roughly, the general order of magnitude of the ratio of gain at Conowingo to loss at Holtwood was about 10 to 1.

Those studies were made on the assumption that both projects would be controlled by the same interests. Later when the Conowingo project was undertaken by the Philadelphia Electric Company, engineers of both companies made exhaustive studies and again showed that there was a very considerable gain to be accomplished by maintaining a pond level at Conowingo considerably higher than would be allowable under a scheme which would permit no interference with levels at Holtwood, or under a scheme adhering to the provisions of certain agreements made years before. A dam of this type is logically a movable-dam proposition, as property or flowage rights must be acquired anyway to elevations above the maximum flood levels. Also when the Conowingo engineers adopted the lower site at Conowingo it was found that a movable dam or gates of some type were almost necessary, or at least economical, in order to hold down the pond level at time of maximum flood to such an elevation as would permit a feasible railroad grade from the Conowingo dam down to Perryville.

An arrangement was finally entered into between the two companies whereby the lower company maintains a pond level not to exceed 108 1/2 ft. above mean sea level. This amounts to a sale of raw water power, you might say, from one company to the other, and I think both companies are going to account for it as a sale of power. The lower company pays the upper company its loss (meaning the loss under the present tailrace conditions, and not the greater loss which would have obtained if the excavation had been carried out) plus a share in the gain at Conowingo. It is a good proposition for both companies, and obviously it is in the interests of conservation of natural resources, because the desideratum is to get the most possible energy out of the Susquehanna River from the Holtwood pond to the Conowingo tailwater, and various computations have shown, depending upon what assumption is made, that the over-all, average net annual gain is from 84,000,000 to over 100,000,000 kw-hr.

Now the overlapping of heads between plants on the same stream, and operated by the same company, is not new, as it has been practised by several companies in recent years, but I believe that such an arrangement between two independent companies is unique, and it is gratifying that what was evidently a good engineering proposition could be put through in a business way.

The Gould Street engineers state that they adopted 440-volt auxiliaries in order to eliminate having two voltages and because the cost of the motors was actually less. I wonder if Mr. Hentz would care to say something on that.

As to the economic side, these papers make the situation clear. Before the Conowingo project was carried out there was available in the lower Susquehanna, from Holtwood down, a fall of about 100 ft., most of which was capable of development, but such development would be economical only if a market could be found which, first, would be large enough to permit of a great over-development of the river as compared with what is generally called firm power; second, would be large enough to absorb practically all of the available output from the start; and, third, with a load sharp enough to give the hydro plant a high-capacity value. Baltimore, with a large existing supply of hydroelectric energy, did not offer such a market. Philadelphia did, especially with the transmission interconnections. It certainly is to the interest of the public that this power which has gone to waste for all time should be developed, thus saving, I believe Mr. Wilson stated, about 750,000 tons of coal a year.

P. L. Alger: I have been much interested in the design of four of the main Conowingo generators. They were so large that they were assembled completely at the plant, and no tests were made at the factory. I am glad to say they have gone into service without any important difficulty, and seem to be operating very well.

One of the novel features of the design of these machines is that the rotor rims are made of overlapping steel plates wrapped flatwise around the periphery, and the rotor spider arms are made of steel plates riveted together, so the entire rotor, except for the hub casting, is of plate construction. This is the first time, I believe, that such a construction has been employed. It has been described in a recent A. S. M. E. paper¹.

After the tests on the machines are completed, we hope to publish a paper giving the general dimensions and details of performance. At the present time, our expectations are that the efficiency at full load and 0.9 power factor under rated conditions, will be 97.5 per cent, although the short-circuit ratio is exceptionally high, approximately 1.4.

D. W. Roper: I should like to inquire from the authors of the papers if there were any special features in the contract which offered an inducement to the contractors to make speed?

A. F. Bang: I wish to offer a slight criticism of the high-tension switching layout at Conowingo. It may have been the

1. H. G. Reist, "Plate-Steel Rotor for an Electric Generator." Paper presented at the Spring Meeting, 1928, of the A. S. M. E. at Pittsburgh, Pa.

most economical layout for the present to put all switches on top of the roof, but it seems to me that such an arrangement very decidedly limits the expansion possibilities. This would be especially undesirable in case at some future time it should be considered important to tie in another high-tension circuit, besides those going to Philadelphia.

Another questionable feature seems to me the ever present danger of oil-switch fires. These will happen occasionally, as we all know, even with the best of modern switches. And in case they do happen, is there not appreciable danger to the extremely valuable equipment below, at least far more so than in a layout where the switching station is at some distance from the power house?

Alex. Wilson: As to the speed with which the construction work was completed, there were several contributing factors, one of which was good fortune in respect to damage and delays due to floods. While two of the floods which occurred during the period of construction exceeded the previous records for the respective months in which they occurred, the condition of the construction work at the time the floods occurred was in such shape that but little damage was done.

Another and probably the most important factor contributing to the speed of construction was the careful scheduling of all operations and rigid adherence to the schedules. These schedules went into great detail, scheduling issue of drawings and the ordering and delivery of material, as well as the actual operations of construction; the calendar period in which each operation must be performed was likewise clearly defined and from time to time as the work progressed, the progress schedules were revised and where gains were made in any of the major operations, the schedule of such operations was advanced.

No bonuses were offered to the contractors to make speed. All of the contracts were agency agreements under which the contractor received a fixed fee for his services.

Mr. Alger referred to the efficiency of the generators. The efficiency of the water wheels might also be of interest. At best gate, these wheels have an efficiency of about 92 per cent.

R. S. Hentz: Mr. Bang has asked why we put the substation at Conowingo on the roof. That was primarily a matter of economics. The contour of the land was such that we could not have erected a substation in any other place except by going up on top of the hill where a double-bus substation could be erected. We believe a fair degree of flexibility has been incorporated into this 220-kv. layout. There is provision for one more 220-kv. line, making three in all. As two lines will easily transmit the contemplated maximum ultimate development of the station there was no need to provide for further expansion. True, it would have been better to have had a double-bus layout similar to that at Plymouth Meeting, but it would have cost too much at Conowingo. Plymouth Meeting, in addition to controlling the power from Conowingo, also controls that from the interconnection, thereby making it of greater importance and fully justifying a double-bus layout.

In regard to the matter of oil fires, when a satisfactory switch

is developed, not using oil, we will be very glad to look at it. However, oil switches are with us and we have to use them. In the case of the 13,800-volt switch structure, the building has been divided into several compartments by smoke-proof barriers, thus confining any oil fires that may occur.

In regard to the lightning arresters, there is one other factor I think was not touched upon. The generators are provided with over-speed and over-voltage devices, (the over-speed is mechanical). These two devices have their contacts in parallel, so that the closure of either will trip the generator breaker. This is necessary to protect any motor driven equipment that might be left on those machines from damage due to excessive speed. This also protects the lightning arresters from very high voltages.

P. H. Chase: I was asked to say something about the lightning situation and the selection of the ground wires on the transmission lines. This matter of ground wires received consideration from many different angles. When we first started there was no operating experience with 220 kv. to help us on the lightning conditions in the East. The initial decision was to omit ground wires. However, before the project was very far under way there was some operating experience in the East, in northern Pennsylvania, and also considerably more information was developed from theoretical and experimental work which indicated the advisability of installing ground wires. The decision was therefore made to include ground wires. There have been various estimates as to how much the induced voltage would be reduced by the use of ground wires; as high as 50 per cent has been talked of. The percentage reduction in voltage is still largely a matter of speculation. I think that in another year we will be able to give quite conclusively the results as they affect operation. We have been through one lightning storm this spring that crossed the line without causing any trouble.

Mr. Hentz mentioned a high-voltage test. Observing the line during this test I was quite surprised that it didn't show much visible corona at 380,000 volts. There were streamers, spots along the conductor, and looking along the conductor one could see a bluish haze. Also there was a slight amount of corona on the line end of the strings. Photographs were taken of the insulator strings with quartz-lens cameras, taking advantage of the ultra-violet rays, but very little corona was in evidence.

It may be of interest to hear of a few questions that have come up since the line has been in service. A few weeks ago we got a complaint from one town that automobiles passing under the line were being "charged," and also that there was serious trouble with radio reception. It turned out that all those were unfounded and simply made good newspaper stories. The starting point was apparently trouble from some trolley circuit or something like that. Complaints have been received that the wires are dangerously close to the ground. When you stop to think of it, to the layman a conductor $1\frac{1}{2}$ in. in diameter looks considerably nearer at 30 ft. than, say, a No. 6 A. W. G. wire.

Those were very amusing, although they had to be met and answered when our publicity people called them to our attention.

The Communication System of the Conowingo Development

BY W. B. BEALS¹

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and

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Synopsis.—This paper describes the communication system which has been installed to serve the power plant at Conowingo, Maryland, and its associated transmission line.

The important features to be considered in designing a telephone system for a power plant are pointed out. The types of telephone switchboard and telephone instruments chosen in this case to meet the special requirements of the generating station,

together with the layout and cabling arrangement, are outlined.

The paper also discusses the possible ways of providing for the needs of the load dispatcher and the plan adopted at Conowingo; the facilities provided the patrolmen for calling from points along the transmission line; the connection from the private branch exchange to the general telephone system; and the special electrical protection installed on the long lines leaving the power house.

1. INTRODUCTION

THE proper functioning of a power plant and distribution system depends to a large extent upon the ability of the operating force to communicate easily and promptly with one another. Therefore, the details of design of a power system may be influenced by a consideration of the various possibilities of telephone communication.

The design of a telephone system to meet the needs of a generating station such as that at Conowingo and the transmission network associated with such a system, requires the closest cooperation between the power and telephone engineers and a thorough understanding of each other's problems.

Among the important features to be considered in this cooperative work are:

- a. Continuity of service.
- b. Means for quick communication with any part of the generating station.
- c. Location of telephones so that they can be used without taking power-house employees away from their working stations.
- d. Means for communication between the generating station, system operator, and points along the transmission line.
- e. Protection for the circuits connecting with the general telephone system.

All of the features in the above list were given very careful consideration in designing the telephone system for the Conowingo project.

The essential elements of such a telephone layout consist of a private branch exchange switchboard which provides convenient means for connecting a telephone in one part of the plant with a telephone in another location or with telephone central offices; telephone distribution cables running from the switchboard to the

locations where the telephones are installed; circuits running from the branch switchboard to the central office of the telephone company; and finally, the telephones themselves so located as best to meet the needs of the people who are to use the system.

2. PRIVATE BRANCH EXCHANGE AND ASSOCIATED POWER PLANT

(a) *Conditions to be Met and Type Adopted.* The Conowingo power house is located within the area served by the Darlington, Maryland, Central Office. In the Darlington central office area, the service is of the magneto type (*i. e.*, hand generators are used for signaling and dry cells are installed at each telephone set to supply talking battery). In such an area it is usual to furnish private branch exchange equipment of the same type. At the Conowingo power house, however, in view of the size of the installation and the fact that it lends itself better to some of the rather special arrangements needed at certain places in the power house, it was decided to use the common battery type of telephone system where the telephone user signals the operator by simply lifting the receiver off the hook.

The adoption of the common battery type of private branch exchange in the Darlington central office area necessitated certain modifications in the usual type of switchboard in order to furnish lamp signaling and supervision and at the same time to operate on connections to the magneto central office switchboard at Darlington.

The operating battery consists of eleven cells of the enclosed radio type and is kept in a fully charged condition by a small, full-wave rectifier, operated from the local lighting circuit and adjusted to trickle charge the battery continuously. The battery has sufficient capacity to operate the telephone system for some time in case of trouble with the rectifier or the local lighting circuits.

Regular and emergency ringing interrupters are installed for supplying energy to ring the various tele-

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phone stations and the central office of the telephone company. A hand generator is also installed in the switchboard for emergency use.

Alarm signal equipment, consisting of a bell and lamps, is provided to indicate the operation of a charge or discharge fuse on the battery, the failure of the a-c. service or the burning out of a rectifier tube. Spare fuses and rectifier tubes have been conveniently located for replacements in case of failure.

(b) *Location and Layout of Private Branch Exchange Equipment.* The private branch exchange switchboard is installed in the main control room and adjacent to the power switchboard operator's desk, so that it can be operated by the power switchboard operator when desired. It is equipped for handling 70 common battery lines, 10 local battery lines and 5 central office trunk or long tie lines (such as lines to Philadelphia). Provision has been made for further trunk and tie line growth.

In the usual private branch exchange all relay and signaling equipment is contained in the telephone switchboard framework. The modifications at Conowingo required a number of additional relays and repeating coils which the switchboard would not accommodate. These relays and coils have been mounted on a small rack similar in design to those used in small telephone central offices. Since the ultimate layout of the main control room would not permit the installation of this rack adjacent to the telephone switchboard, it has been placed in another room as close as possible to the board.

From the telephone switchboard lead-covered cables extend to a cross-connecting main frame which permits the association of any cable pair in the distributing cables to the telephone stations, or, in the cable leading out of the power house, with the proper switchboard terminal. The distributing frame is of the type used in small telephone central offices and carries the standard telephone protectors. It has been located in the same room assigned to the telephone power plant. This room is close to the center of distribution of the telephones which will ultimately be needed and will, therefore, permit of the most economical distribution cable layout.

3. TELEPHONE STATION EQUIPMENT AND DISTRIBUTION CABLE

(a) *Requirements and Types Adopted.* As mentioned previously, the main requirements of the apparatus to be installed in the power station are simplicity of operation, durability and compactness. The first of these has been met by the adoption of common battery signaling equipment. To meet the second and third conditions the telephones have been placed in recessed cabinets in the walls. Each cabinet is designed to hold a standard desk stand and bell box and is provided with a door which lets down to serve as a

shelf when the telephone is in use. When the telephone is not in use, the door is kept closed and the apparatus is out of the way in a protected location. This method of installation is general in the power stations and substations of the Philadelphia Electric Company.

At the gage board at each of the machines, under certain conditions it will be necessary for attendants to take orders over the telephone, read the meters, and adjust apparatus at the same time. In order to meet this condition and still avoid the possibility of having telephone apparatus in a position where it might be in the way, a jack has been provided at each of the gage boards, and operators' telephone sets with chest transmitters and head receivers with extension cords have been provided in convenient locations for use with the jack ended circuits. The jacks are enclosed in dust-proof boxes and are connected to two circuits terminating on the switchboard, one circuit terminating at the panels for service generators Nos. 1 and 2 and main generators Nos. 1 to 4 and the other circuit at the panels for present and future main generating units Nos. 5 to 11. With this arrangement the station attendants can talk over the telephone and yet have both hands free for whatever they are required to do.

Telephone stations have been provided along the dam for use in making reports from points in the vicinity of the gates. Since these stations are in locations which will always be subject to a certain amount of moisture, mine type sets have been installed in recessed cabinets located at convenient points along the parapet wall. These cabinets are provided with metal frames and covers and are kept locked in order to prevent use of the telephones by unauthorized persons. Mine type sets have also been provided on the observation platform near the spillway and in the inspection tunnel in the vicinity of the butterfly valves.

Five mine type sets have been installed on the steel framework of the substation located on the roof of the power house, some points of which are 85 ft. above the level of the roof. They provide a means of communication with men working on the 220-kv. disconnecting switches. Four additional mine type sets have also been installed at various locations on the roof of the power house. In addition to these telephones, four jack-ended circuits have been mounted inside of the mine type sets on the roof. Durable, moisture proof extension cords terminated at one end in a plug for connection to the jack-ended circuits and at the other end in a small jack box have been provided for the use of men working on the inside of the 220-kv. circuit breaker tanks. The jack boxes are arranged to be attached to the workmen's belt in order to leave both his hands free. A regular telephone operator's set with a short cord and plug is provided so that the workman may insert the plug in the jack box on his belt. This gives an easy means of communication between the men working in the circuit breaker tanks and men outside.

In the office bay, standard desk set equipment has been provided for office employees.

(b) *Cabling Layout.* In view of the conditions to be met in rendering telephone service in power stations, the telephone circuits are for the most part in lead-covered cable except that the runs from cable terminals to the individual stations are made with single pair twisted wire. These cables vary from 11 to 101 pairs each and are run through metal conduit, installed for this purpose when the concrete of the structure was poured. The telephone conduits are separated by several inches from the conduits carrying lighting and other distribution circuits in the power house, and are bonded to the power system ground so that in case of any faults on the power circuits it is expected that resulting voltages and stray currents will not introduce a hazard on the telephone circuits. The installation of telephone cables of the size employed in the power house necessitated placing "pull boxes" at frequent intervals along the conduit runs.

The distribution cables to the stations are terminated in five main terminal boxes where the individual cable pairs can be connected to the wires running to the various stations. This permits of considerable flexibility in cable pair assignments, and makes it possible readily to interchange cable pairs in case one becomes defective or to replace a short section of cable without interfering with the rest of the circuits in the telephone plant.

4. OUTSIDE LINES

(a) *Trunk Lines and Outside Stations.* The private branch exchange is connected with the telephone company's central office at Darlington, Maryland, by means of two circuits which are carried out of the power house in lead-covered cable and thence by open line wires to the central office. The same cable carries a few lines to stations located in the employees' houses not far from the dam.

(b) *Load Dispatching Circuits.* In any power transmission system the operations requiring coordinated action at power sources and substations make it imperative that communication be established quickly and maintained without interruption between the load dispatcher and the operating units.

As the system is extended to include more than one source of supply the necessity for this close supervision on the part of the load dispatcher is very greatly increased by the need for proper distribution of loads. This supervision may be secured by automatic operation or through communication with an operating force.

At the A. I. E. E. Midwinter Convention in Philadelphia in February 1924, two papers were presented describing apparatus for distant operating by mechanical means. The use of this equipment places in the hands of the load dispatcher the means of regulating generators and loads by his own personal actions and in certain cases generating plants and substations can be very satisfactorily operated in this manner. Associated with the mechanical operation of these systems

there must be visual indication of their conditions by such means as distant metering, gaging, etc.

With power units and substations of such size as are involved in the Conowingo project, personal attendance becomes imperative for a number of reasons, and therefore system operation from a distant point through mechanical agencies was deemed not suitable for this installation.

Several methods which present themselves, *viz.*, telephone, telegraph, and printing typewriter were considered in setting up the load dispatching system for the Conowingo power project. The extensive existing load dispatching system of the Philadelphia Electric Company system had a great influence in deciding what extensions should be made to care for the interconnection with the Conowingo project. This existing system consists of private lines leased from the telephone company and connecting the various substations and generating centers with the general office building of the company. At this location the lines terminate in a magneto switchboard in the office of the load dispatcher who can thus secure instant direct contact with the various units of the system.

This system is reserved for the exclusive use of the load dispatching forces and no connection is provided to the telephone company's exchange system except through an emergency circuit on the board in the load dispatcher's office.

Direct telephone company facilities were, therefore, found most suitable in the extension to Conowingo of the load dispatching system. In planning this extension, two prime factors were considered to be highly important, continuity and reliability of service. To provide for the former, it was decided to supply both regular and emergency circuits routed through separate cables or over separate pole lines so that in the event of ordinary maintenance troubles which might affect one circuit, the second would be available. The reservation of both of these circuits for load dispatching exclusively is not warranted, and provision is made for one to be used between the private branch exchanges provided for general telephone business, but to be available to the load dispatcher by means of loop jacks in his private line switchboard. This latter arrangement permits the load dispatcher to take over the use of the second circuit and clear any conversation that it may be carrying.

The second requirement, reliability, presented the more difficult engineering problem, as it will in any similar situation. The telephone company had existing plant for the entire distance from the Conowingo site to the headquarters of the Electric Company at 10th and Chestnut Streets, Philadelphia, consisting of underground cable plant between Philadelphia and Havre de Grace at the mouth of the Susquehanna River connected to an open wire pole line from Havre de Grace to the power site. Underground plant is, of course, most reliable, but the open wire line may be interrupted during heavy sleet and wind storms.

The power company has a continuous private right-of-way from Conowingo to Plymouth Meeting. This right-of-way is free from trees and other obstructions, but proximity to the high-voltage transmission line rendered it unsuitable for communication circuits.

Various means of securing telephone service were studied, including carrier current systems on the power transmission lines and short wave radio. At the time this paper was prepared, consideration was being given to the desirability of building a new pole line on a private right-of-way, cleared of trees and shrubs, from Havre de Grace to the power site. The poles and wires would be so spaced and of such strength as to be capable of withstanding ice and sleet loads such as have been encountered in the past.

While load dispatching is of prime importance in setting up communication service, there are other important uses which cannot be neglected. Many routine matters of operation and maintenance can best be handled by telephone and facilities to do this must be provided. Many power companies do not feel that it is necessary to reserve the dispatching circuits exclusively for that service and use the same circuits for the transaction of general business. However, with the demand on the power companies for continuous service by trunk line railroads and city water supply systems, etc., the necessity of immediate communication for load dispatching purposes becomes more exacting. For this reason the Philadelphia Electric Company decided to provide a second circuit to care for general business and make this second circuit available in emergencies for load dispatching purposes as outlined above.

(c) *Patrol Stations.* Another important communication service is that provided for the use of patrolmen. Regular telephone service by means of telephone stations connected to the nearest central office of the telephone company offered opportunity for patrol service over the regular toll lines of the telephone system. With the increased speed of service now provided over these lines dependable and rapid connections can be obtained. This method has the advantage over a single patrol circuit, in that in case of failure of one toll line, alternate routes are available. If the number of patrol stations is small and the calls infrequent, this service is also less expensive.

This method was adopted for the Conowingo system and four patrol stations have been established between Conowingo and Plymouth Meeting, each with the telephone located in a building owned by the Power Company and located on its right-of-way.

(d) *Special Protection.* Preliminary computations indicated that at time of fault on the 220-kv. transmission line, ground currents of considerable magnitude would flow through the station ground connection, and even if the impedance of the ground connection were as low as a fraction of an ohm, there would be a considerable rise in ground potential in the neighborhood of the dam.

A rise in ground potential at the dam with reference to the ground at the other terminals of the circuits connected to the private branch exchange might operate the telephone protectors and result in interruptions to telephone service at times when it was most needed. These potentials would also be effective between the telephone circuits and ground in any location outside the area affected by the power system ground.

Since all metallic structures in the power house are thoroughly bonded to the same ground; no potential will exist between telephone equipment and other metallic structures in the power house unless the telephone be connected metallically to a circuit extending outside the area within which a considerable difference in ground potential is caused by the fault.

Due to the extensive grounding system, consisting of ground plates, water pipes, the steel reinforcement of the dam itself, and numerous other metallic structures in the power plant, the most practical method of avoiding interruptions to service coincident with failures on the power line seemed to be, in this case, to isolate the portions of the long circuits within the area in which potentials considerably different from outside points might be expected.

Tests were made jointly by the power and telephone interests to determine the impedance of the power system ground connection and the extent of the area which might be at potentials substantially different from those at distant points. These tests were made by feeding current through a ground established at some distance from the power station back to the power station ground and measuring the difference in potential between the power station ground and the telephone central office grounds at Darlington and Belair, Maryland, as well as at intermediate points. These tests indicated that the impedance of the power system ground was at that time between $4/10$ and $5/10$ of an ohm and that the potentials of points along the west bank of the river and in the Stone and Webster company's construction camp close to the dam varied only about three per cent from the potentials impressed on the power station ground. It was also found that the potential of the water system in the power company's village about 3000 ft. from the dam was only about 6 per cent lower than the potential at the dam and that the potential at points in the village about 100 ft. away from the nearest water pipes was only about 15 per cent different from the potential at the power plant. Further measurements indicated that the earth potential gradient along the telephone line toward Darlington central office was quite gradual and a slight rise in potential was noted even at the Darlington central office, more than two miles from the dam.

A point about a mile away from the dam at the edge of the power company's property where the circuits to the private branch exchange leave the telephone company's line was selected as the most practicable location for insulating transformers to be used in isolating the

telephone plant in the area within which substantial rise in ground potential might be expected. The measurements indicated that about 65 per cent of the total drop in potential occurred between this point and the power station ground.

Western Electric Company's No. 50-A repeating coils, insulated between windings for 25,000 volts, have been installed at this point, with lightning arresters on both sides of these coils. The breakdown voltage of these arresters is such that they will not be operated by any rises which it is expected may occur in the potential of the power station ground.

CONCLUSION

As indicated above, the proper functioning of a power plant and distribution system depends to a considerable extent upon the provision of an adequate communication system by means of which the operating forces can promptly and easily communicate with each other.

In many cases the provision of such a communication system requires the solution of numerous special problems and these are illustrated in this paper by the special problems involved in the design of the communication system of the Conowingo project.

Cooperative consideration by power and telephone engineers of all the available means of communication at an early stage in planning the project, and the adoption of the means most suitable in the specific case should result in the provision of a communication plant of the greatest effectiveness in the operation of the power system.

Discussion

E. C. Markley: It is particularly interesting to note the rather extensive internal communication facilities provided at various points around the building and switch structure. In this connection, is it possible to connect any one of the telephone instruments to the trunk line connected to the Philadelphia load-dispatching system?

As regards dispatching communication, Conowingo is particularly fortunate in its location. It is in an area unusually well provided with underground telephone circuits and therefore only relatively short distances of open-air telephone lines need be protected against storm conditions.

In other parts of the country, an entirely different problem is encountered. Where wire telephony is employed in connection with the operation of 220-kv. and other high-voltage lines, underground cable construction is rather prohibitive and therefore communication must be carried on by open-wire telephone lines. Even in those areas where cable circuits may be used to an extent comparable to this section, hydroelectric stations are usually remote from the centers of the cable telephone system. Power companies have therefore resorted to employing their own telephone lines, carrier current, or space radio. These alternatives were mentioned in the paper, but further discussion along those lines might be of interest, as well as such systems as straight telegraph and printing telegraph systems.

W. B. Beals: In regard to the question of the load-dispatcher's circuit being available to communicate with any part of the plant: at the present time the regular load-dispatching circuit is terminated in a telephone, on the station operator's desk, that puts him in direct touch with the load dispatcher's

switchboard in Philadelphia. I mentioned a second circuit which has been installed over another route, which is available for what might be called miscellaneous business, general telephone business, or any business that can best be handled by telephone. That line is connected between the regular board of the private-branch exchange—not the load-dispatcher's board—of the Philadelphia Electric Company in Philadelphia and the private-branch exchange at Conowingo. That circuit is available for communication with any of the stations located in various parts of the plant. Furthermore it can be taken over by the load dispatcher and used as an emergency circuit in case of interruption on the regular load-dispatching circuit.

In regard to the telegraph, I think I mentioned that one of the factors that led to the use of telephone facilities was the fact that the Philadelphia Electric Company now has a rather extensive telephone load-dispatching system, and to apply that method of communication to tie-in Conowingo meant simply an extension of the existing system. The printing telegraph, of course, is of very great importance and convenience in case it is desired to keep a record of all orders issued.

E. B. Tuttle: In laying out the communication system, this entire interconnection was carefully studied so that any communication circuits which were set up in connection with the Conowingo-Plymouth Meeting part of the system, would be properly coordinated with future possible extensions. That, I think, is one of the particular advantages of making such a communication study very thoroughly in the preparation of the plans for a power system. I should like to add my word to the thought that the power company engineers are fully conversant with their requirements, with what their system needs in the way of power transmission, and also with their needs for communication to a very large extent. Communication engineers, on the other hand, should be in a better position to design what communication facilities are required, particularly if these involve rather extensive interconnection circuits, and so it is particularly fortunate that in connection with this Conowingo job the communication engineers were able at so early a date to assist in the preparation of the system. This is going to be particularly true in the future and even today because of the large increase in the extent of the power system interconnection service. Load dispatching in the East which today may cover 50 miles from a single load dispatcher who would control perhaps all of the system will extend in the course of a few years to hundreds of miles. So it will be of particular advantage to both power and communication companies for communication engineers to be consulted in connection with communication requirements.

The thought was expressed by Mr. Markley that the Conowingo Project was particularly fortunate in its location close to underground communication cables. It may be of interest to note that in setting up the entire project for this intercommunication system about 400 miles of communication circuits appeared to be necessary, and of that not more than 50 miles is in territory where open-wire construction is necessary. The aerial cable as well as the underground cable plant of communication systems are being extended with very great rapidity. During a discussion of this subject with some communication men in Ohio the thought was expressed that the power companies in Ohio did not perhaps feel the necessity for instantaneous communication as did the power companies in Philadelphia, and I could not help expressing the thought that although that might be so at the present time it would not be for long, but that the communication companies might grow in stormproof facilities, about as rapidly as stormproof facilities are demanded. I may be a little optimistic on that subject, however.

In this particular interconnection study, there is one section of 25 miles of open wire required in order to reach the power house, and it is proposed to make that open-wire line of such a strength as will stand any sleet storm recorded to date. The

price is not excessive either when constructed on a power line or a communication line.

Mr. Markley expressed an interest in the application of carrier current in connection with load-dispatching systems. The use of carrier current on power lines is a question of economics and continuity of service. Those two points are the prime reasons. It has been pointed out in the papers that when additional emergency service is desired, carrier current may furnish that service. Certain costs in the way of depreciation, interest on the money invested, maintenance, and operation must be taken into consideration, and in the case of the Conowingo-Philadelphia route these amount to very much more than the the annual expense of a leased communication service; and ample facilities were available for emergency routes.

Short-wave radio may also provide, in a similar way, for such continuity of service. At the present time there is extremely little known of the operations of short-wave radio over land for distances under two and three thousand miles. We know, from experiments and studies that have been made, what can be expected of short-wave radio over long distances such as those and for short distances over water, but no experiments of any considerable amount have ever been carried on over land for short distances. We do not know what the effects of electric storms will be, particularly in this part of the country,—and Philadelphia, I believe, is nearly the worst electric storm area we have in the United States. For that reason all you can say for space radio at the present time is that it is experimental. In the course of a few years, additional information will be available and definite recommendations can be made.

Mr. Beals referred to the use of printing telegraph and that brings a very interesting thought to my mind, something on

which the communication companies would like to hear some discussion at some time, and that is, what relation does the usage of load-dispatching circuits have to the necessity for printer telegraph or some other recording device. For instance, where the load dispatcher's circuit is assigned exclusively to load-dispatching purposes, as is the case with the Philadelphia Electric Company, there seems to be no desire on the part of the electric company at the present time, at least, for records of the orders passed. Certain other power companies who have their load-dispatching circuits used also for the transmitting of general routine business seem to find it desirable to have a permanent record of all orders passed for load-dispatching purposes. Whether there is any relation between these two facts, I do not know, but I should like to hear some discussion along that line.

R. A. Hentz: I can only reiterate what Mr. Beals and Mr. Tuttle have said about the load dispatcher's telephones. The importance of reliable communication is so great that the best was desired—and the cost was not excessive. While we are experimenting with short-wave radio, the results to date have not been reliable enough for this service.

C. A. Allner: Referring briefly to the last point mentioned by Mr. Tuttle, both can be suitably combined by hooking up a dictaphone to the telephone as has been the practise on the Pennsylvania-Baltimore System for over ten years.

E. B. Tuttle: That has been done in some cases, but engineers who have been working with it find that while certain features are very satisfactory, there are certain other features which are not, due to the load dispatcher's having to change records in the middle of his conversation.

Quantitative Mechanical Analysis of Power System Transient Disturbances

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Non-Member.

Synopsis.—The quality of service that can be rendered during unavoidable system transients produced by short circuits must be given careful consideration in the analysis of proposed interconnection and transmission projects. An analysis of present systems that have grown until such limitations have apparently been reached, will frequently reveal comparatively inexpensive changes in equipment or operating practice which will permit good service to be given and defer large investments in additional lines for a considerable period.

The fundamental mathematical methods for calculating system transients have been presented by other writers during the last few years. These mathematical calculations are of necessity quite involved and consequently can only be applied to very simple power systems. The calculations must be made by thoroughly experienced engineers and the results are not readily understood by the operating staff.

In the May 1926 issue of the *Electric Journal*, under the title "A Mechanical Analogy to the Problem of Transmission Stability," Mr. S. B. Griscom proposed the use of an accurate equivalent mechanical analogy to the electrical system provided perfect springs for representing line reactance could be obtained. A simple mechanical model for qualitatively illustrating the fundamental principles has been demonstrated before various local A. I. E. E. sections and has resulted in a wide general knowledge of the transient behavior of power systems.

The present paper covers the adaptation of the mechanical model

principles to obtain reasonably accurate quantitative records of transients to be expected on the 220-kv. interconnection between the Philadelphia Electric Co., Pennsylvania Power & Light Co., and the Public Service Electric & Gas Co. These records are obtained by taking motion pictures of the equivalent mechanical system. Resistance or reactance short circuits on transmission lines are duplicated mechanically by applying forces of the proper magnitude and direction to the spring representing the line in trouble, and clearing this spring at each end by blowing fusible links from relays timed to represent the circuit breaker operations on the electrical system. The resulting mechanical oscillations will correspond to those of the electrical system because the inertias, spring characteristics, and torques of the mechanical model elements have been proportioned to the corresponding elements in the electrical system; namely, stored energy, reactance, and kilowatts. The inherent limitation due to imperfect springs has been overcome sufficiently to give results that are accurate within practical limits.

It will be shown that the actual setting up of a system on the mechanical model is comparatively simple, and does not require a great deal of experience or mathematical skill. Slow motion pictures of the disturbance can be taken with amateur cameras that are available on the market, and curves of the oscillations plotted from the projection on a screen. The slow motion pictures can be used also for acquainting the operating staff with the effect of various types of disturbances on the system, and for determining the most advantageous sequence of relay operations.

FUNDAMENTAL PRINCIPLES OF THE MECHANICAL ANALOGY TO THE ELECTRICAL SYSTEM

THE analogy between the various parts of the electrical system and the equivalent mechanical system are shown in Fig. 1, which represents single generator and its load tied together by the system reactance. The model consists of a generator element and a motor element, mounted on ball bearings and free to rotate independent of each other. For the present, the fault element should be neglected. The rotors have inertia proportional to the stored energy in the generators and loads which they represent. Each element is balanced, and when free from the system and the torque representing generator input or load, is in a state of equilibrium in any position. The weight (a) produces a torque, tending to rotate the generator element in a counterclockwise direction, and the weight (b) produces an equal torque, tending to rotate the motor element in the opposite direction. At synchronous speed, the input kilowatts (torque *a*) to the generator are exactly equal to the output kilowatts (torque *b*) at the load, and the model will be

stationary. For any disturbance which suddenly increases the kilowatt load on the system without the governors having time to make a corresponding increase in the generator input, the model will rotate in a clockwise direction, indicating a decrease in frequency. The unbalanced torque (kw. loss in fault) must be absorbed by the inertia of the system and on the mechanical model, will produce oscillations between the relative positions of the two arms similar to the oscillations between the two ends of the electrical system.

With fixed internal voltages in the synchronous machines at the two ends of the system, the phase angle between these voltages plotted against power transmitted is a sine curve similar to Fig. 2 for a purely reactive tie between the ends of the system. The ratio of resistance to reactance of most systems is so small that the resistance may be neglected in making transient analysis without excessive error. The system having power-angle characteristics as in Fig. 2 will pull out of step if the load is gradually increased until the angle between the ends of the system is 90 deg. This is known as the steady-state pull-out limit. When the power being transmitted corresponds to point *a* in Fig. 2, a system disturbance that does not cause the angle to increase beyond point *b* will not cause pull-out.

1. Both General Engineers, Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

Presented at the Regional Meeting of District No. 2 of the A. I. E. E., April 17-19, 1928, at Baltimore, Md.

It is, therefore, possible to have angular swings between the ends of a simple two-element system that considerably exceed 90 deg. without loss of synchronism. It should be noted that a change in the internal voltages of the machines in the electrical system, or a corresponding change in the lengths of the arms on the mechanical system, will modify the power-angle characteristics of the system.

CONVERSION OF ELECTRICAL SYSTEM INTO MECHANICAL EQUIVALENT

The first step is to determine the characteristics

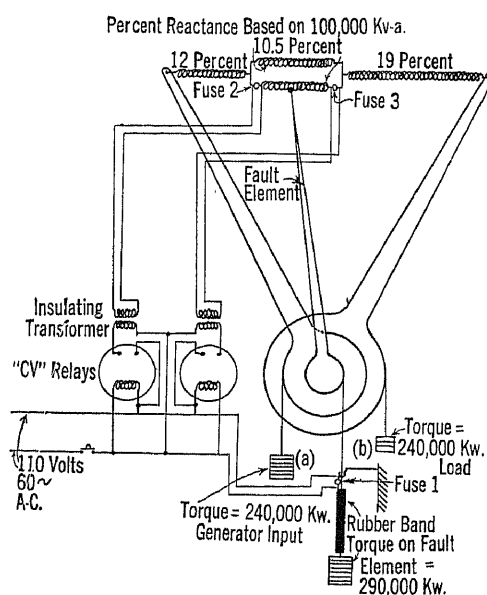


FIG. 1

Mechanical Analogy	Transmission System
1. Stiffness of spring.	1. Reactance represented.
2. Length of spring.	2. Voltage drop across reactance represented by spring. It is proportional to line current.
3. Counterclockwise torque applied by weight to any element	3. Represents kilowatts generator input to system at that point on system.
4. Clockwise torque applied by weight to any element.	4. Represents kilowatts load taken from system at that point.
5. Radial distance from pivot to any point on spring.	5. Line voltage at corresponding point.
6. Product of length of arm and component of spring tension along radius.	6. Reactive Kv-a.
7. Angle between any two points on the spring.	7. Electrical phase displacement of voltages at corresponding points of the system.
8. Inertia of any element.	8. Stored energy at synchronous speed in machines constituting corresponding element of electrical system.

of the springs which are to represent reactance. The springs should be chosen so that they will not be stretched beyond their elastic limit when the model pulls out. Under this condition, it is desirable to work the springs as close as possible to their elastic limit so that the initial length will be a minimum. Consider that it is desired to select a spring of 10 per cent reactance on a 100,000-kv-a. base. In the electrical system, the 10 per cent on the 100,000-kv-a. reactance

tie with 100 per cent voltage at each end, will correspond to a steady-state pull-out limit of

$$\frac{100 \text{ per cent}}{10 \text{ per cent}} \times 100,000 = 1,000,000 \text{ kw.} \quad (1)$$

The corresponding pull-out torque T of the mechanical model should then be obtained by gradually adding equal weights to the generator and load elements until the steady-state pull-out at 90 deg. between arms is obtained with the spring which is to represent 10 per

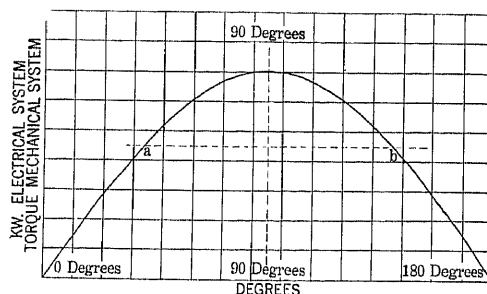


FIG. 2—ANGLE BETWEEN E_r AND E_s IN ELECTRICAL SYSTEM
ANGLE BETWEEN GENERATOR AND MOTOR ARMS IN MECHANICAL SYSTEM

cent reactance connected to each arm L inches (representing 100 per cent system voltage) from the pivot. This torque T (in ounce-inches) is then equivalent to 1,000,000 kw. on the electrical system.

The springs representing the reactances of the other parts of the system are then proportioned, taking the above spring as a base. Under the pull-out condition,

the force in the spring is $\frac{1.41 T}{L}$ ounces. This force

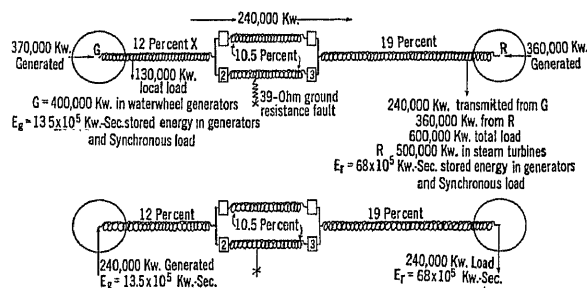


FIG. 3—(SEE FIG. 1 FOR SET-UP ON MECHANICAL MODEL)

elongates the 10 per cent reactance spring to $1.41 L$ in., or would elongate a 1 per cent reactance spring to $0.141 L$ in. A one per cent reactance spring then can be determined by the fact that it assumes a

$$\text{length of } 0.141 L \div \frac{1.41 T}{L} = \frac{L^2}{10 T} \text{ in. when a}$$

weight of one ounce is hung on it. Now the springs to represent the various reactances of a system can be cut to proper length by hanging on them a one-ounce weight,

(or a fraction thereof, if it is found necessary to use a lesser weight). For example, a five per cent spring should reach a length five times that of the one per cent spring with the same weight applied.

The errors due to springs having a finite initial length can be eliminated through the working zone by winding the springs so that there will be an initial compression between turns. As shown in Fig. 4, the relation between spring length and force is then a straight line beyond the finite length of the spring and if projected, this line would start from zero. In the actual operation of the model, the springs are generally stretched beyond the initial length and therefore have such characteristic that no appreciable error is introduced.

The stored energy in a synchronous machine =

$$E = \frac{2.3 (W R^2) (\text{rev. per min.})^2}{10^7} \text{ kw.-seconds at synchronous speed.}$$

($W R^2$ is in pounds-feet squared) (2)

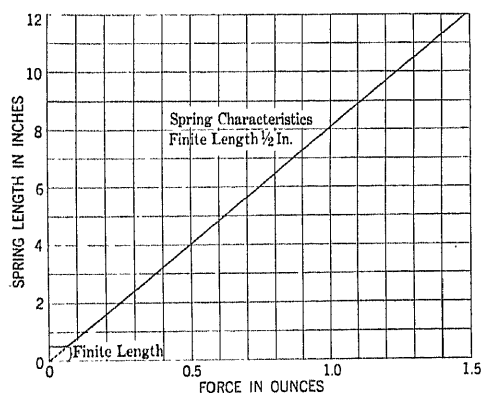


FIG. 4

The total stored energy E at synchronous speed in the machines constituting any particular element of the system may be converted into inertia of the corresponding mechanical model element as follows:

$$W_1 r_1^2 = \frac{E \times T \times 2.05}{10^6} \text{ ounce-inches squared.}$$

E = Stored energy in synchronous machines in kw. seconds.

T = Ounce-inches of torque on model at steady-state pull-out with 10 per cent reactance spring attached to each arm L inches (equals 100 per cent voltage) from pivot. (3)

After determining the spring constant and the inertia in the foregoing manner, it can readily be shown that the natural period of any given element of the electrical system and the corresponding element of the mechanical system are identical. Consider the case of a generator having E kw. seconds of stored energy at synchronous speed connected to a system of infinite

capacity through 10 per cent reactance on a 100,000-kv-a. base. With 100 per cent internal voltage in the generator, the pull-out of this system will be 1,000,000 kw., as previously shown. The kw. required to produce one electrical degree of displacement when the system is carrying enough load to have a 45-deg. angle then will be

$$p_1 = \frac{1,000,000 \cos 45}{57.3} = 12,300 \text{ kw.}$$

per electrical degree. (4)

The natural period of the electrical system at this point then is

$$P = 148.6 \sqrt{\frac{E}{p_1 \times f \times 10^5}} \text{ seconds} \quad (5)$$

$$f = 60 \text{ cycles}$$

Substituting values for p_1 and f in (5)

$$P = 148.6 \sqrt{\frac{E}{12,300 \times 60 \times 10^5}} \quad (6)$$

$$P = 54.3 \times 10^{-5} \sqrt{E} \text{ seconds} \quad (7)$$

In the equivalent mechanical system the torque at pull-out equals T ounce-inches. The torque per mechanical degree of displacement from the 45-deg. position will be

$$T_1 = \frac{T \cos 45 \text{ deg.}}{57.3} = 0.01234 T \text{ oz.-in. per deg.} \quad (8)$$

The natural period of the equivalent mechanical system from the torsional pendulum formula is then

$$P = 0.0422 \sqrt{\frac{W_1 r_1^2}{T_1}} \text{ seconds} \quad (9)$$

Substituting for $W_1 r_1^2$ its value from equation (3) and for T_1 its value from (8)

$$P = 0.0422 \sqrt{\frac{E \times T \times 2.05}{10^6 \times 0.01234 T}} \quad (10)$$

$$= 54.3 \text{ by } 10^{-5} E \text{ seconds} \quad (11)$$

From a comparison of (7) and (11), the natural period of the equivalent mechanical system is identical with that of the electrical system.

The above discussion applies directly to all conditions imposing symmetrical loads on the different phases. For fault conditions, the electrical load may be unsymmetrical; *e. g.*, the fault usually is from one-phase wire to ground. From the stability standpoint, however, a single-phase fault on a polyphase system may be represented accurately by an equivalent symmetrical shunt impedance across the three phases at the point of fault. This was demonstrated by Messrs. Evans and Wagner in their paper *Studies of Transmission Stability*, Appendix III, presented at the Midwinter Convention of the A. I. E. E. Feb. 8-11, 1926.

COMPARISON OF CALCULATED VS. MECHANICAL MODEL TEST RESULTS ON TWO-ELEMENT SYSTEM

Fig. 3-A shows two generating stations, each supplying

some local load and tied together by two transmission lines. Station *G* has a total of 400,000 kw. in water-wheel generators on the line supplying a local load of 130,000 kw. and transmitting 240,000 kw. towards station *R*. Station *R* has 500,000 kw. in the steam turbines on the line carrying a load of 360,000 kw. The remaining 240,000 kw. of the local load being obtained over the transmission system. The stored energy of the synchronous machinery at station *G*, calculated for each item of equipment in accordance with formula (2) total 13.5×10^5 kw. seconds. Likewise at station *R* the total is 68×10^5 kw. seconds.

In setting up a complicated system the number of elements must necessarily be kept down to a minimum in order to reduce the possibility of interference between springs. It is desirable, therefore, to combine the inertia of the local load with that of the local generating station into a single element on the mechanical model. Except for the phase angle which it produces in the generator, the local load has no effect on the over-all phase angles of the system. The simplified system used in setting up the mechanical model and calculating the curves which follow is shown in Fig. 3-B. By combining the load with the generator element, the system has been simplified to only two elements on the mechanical model. Disturbances on such a comparatively simple system can readily be calculated by a point-by-point method for comparison with the test results from the mechanical model.

In setting up the mechanical model, the various springs were proportioned to the reactances of the sections they represent, in accordance with the methods previously outlined. The torque equivalent to the

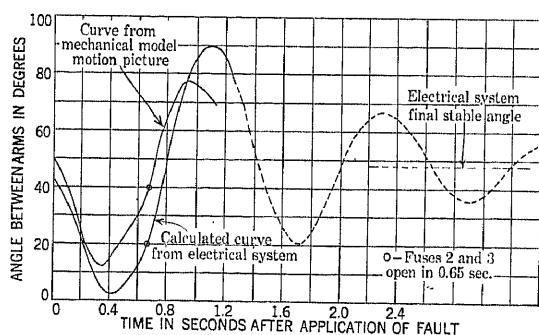


FIG. 5—COMPARISON OF CALCULATED AND TEST CURVES FOR 290,000-kw. line to ground fault on the system shown by Fig. 3A

240,000-kw. load being transmitted was applied to the generator and motor elements tending to turn them in opposite directions, thereby holding the system in equilibrium. The inertia of each element of the mechanical model was proportioned to the stored energy of the corresponding element of the electrical system in accordance with (3), thereby making the natural period of the mechanical system identical with that of the electrical system.

Fig. 1 shows the mechanical model set-up of the above

system. The fault has been assumed to be single-phase line-to-ground, with 39 ohms resistance in the ground circuit. Based on the internal voltages in the machine being practically maintained by means of quick response excitation, the loss in the fault amounts to about 290,000 kw. This is based on internal machine voltages being somewhat higher than the actual transmission voltage, and these higher voltages were also used on the arms of the mechanical model. The power in the fault was converted into equivalent ounce-inches

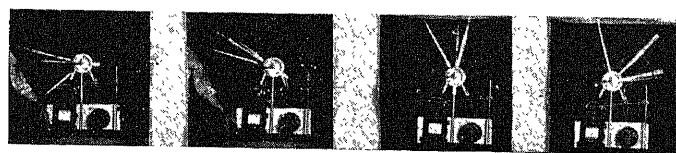


FIG. 6—EXTRACTS FROM MOTION PICTURES OF 290,000-KW. FAULT ON SYSTEM BY FIGS. 1 AND 3

- a. Mount after fuse No. 1 (Fig. 1) is blown, releasing fault arm.
- b. 0.25 sec. after fault. Note the decrease in angle.
- c. 0.60 sec. after fault. Fuses No. 2 and 3 (Fig. 1) beginning to clear the spring which is attached to the fault arm.
- d. 0.75 sec. after fault. Fault arm with spring 2-3 attached to it, has been cleared from the system.

For curves plotted from the motion picture record, see Fig. 5

of torque on the mechanical model, and this torque was suddenly applied to the transmission line on which the fault occurred by means of a very light rotating "fault arm" mounted on a ball bearing as shown in Fig. 1. Here the two ends of the spring representing the line in trouble are tied into the remainder of the system through fusible links which represent the circuit breakers at each end of line 2-3 (Fig. 3-B). The *CV* relays are timed to blow these fuses in the same sequence as the circuit breakers would clear the fault on the actual system. It is not necessary to blow the fuses simultaneously. For example, if fuse No. 2 is blown first, the fault arm immediately swings clockwise and continues to apply the fault through fuse No. 3 and the section of spring representing the reactance of this section of the line. The fuses are blown through insulating transformers so that the current can be kept out of the springs. When fuse No. 3 blows, the fault is entirely removed from the system and the fault arm swings clear with spring 2-3 attached to it, thus removing the unbalanced torque which tends to rotate the model, and indicating a decrease in system frequency. If the disturbance is not sufficiently severe to cause pull-out, the system will oscillate and finally assume a new stable angle corresponding to that when transmitting 240,000 kw., with only one line in service.

By referring to the schematic diagram in Fig. 1, it can be seen that the fault is applied by releasing the weight attached to the fault arm through the blowing of fuse No. 1 immediately after the pushbutton is closed. The closing of this pushbutton also starts the *CV* relays so as to blow fuses No. 2 and No. 3 in the proper sequence.

The weight was attached to the fault arm through

a long rubber band, so that no time would be lost in accelerating the mass of the weight applied to the fault arm. The radius of the hub of the fault arm is so small that the rubber band will have linear characteristics, even with a considerable change in the angle of the fault arm.

In some cases where the fault resistance is low, the positive sequence voltage, which is the voltage represented on the model, will dip to about 67 per cent of normal at the point of fault. In such cases an additional spring was used at the top of the fault arm and released simultaneously with the fault arm, so that the positive sequence voltage would be pulled down to this value.

Fig. 6 shows extracts from the motion picture film of the mechanical model with the equivalent of a 290,000-kw. line-to-ground fault applied to the system shown in Fig. 3-A.

Fig. 5 shows the angle between the generator and motor internal voltages at each instant from the time that the fault is applied. The curve taken from the motion picture of the mechanical model is plotted for comparison with the curve calculated from the electrical quantities of the system by a point by point method. There is a fairly close coincidence between the curves, particularly at the extreme angular over travel after the breaker opened. The mechanical model curve has a certain amount of damping, whereas the solid portion of the calculated curve has no allowance for damping which would actually be present on the electrical system. This particular disturbance shows the mechanical model in the least favorable light, since the high kw. loss in the fault is accompanied

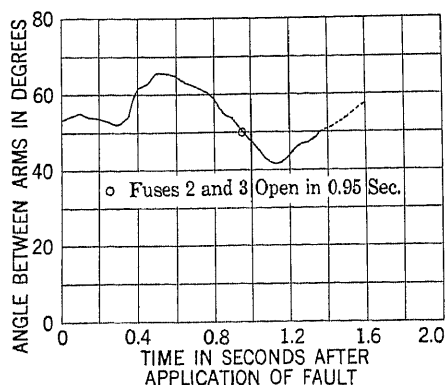


FIG. 7—140,000-Kw.—10 OHM LINE TO GROUND FAULT ON THE SYSTEM SHOWN BY FIG. 3A

by only a small reduction in the positive sequence voltage and causes the comparatively light generator arm to swing toward the motor arm so that the finite length of the spring came into action. The finite length of spring coupled with no allowance for damping in the calculation of the electrical system is responsible for the difference between the minimum values of angle in the two curves.

The fault load must be supplied from the stored energy in the synchronous equipment on the system, causing a decrease in speed, because the disturbance is over in such a short time that ordinary governors cannot come into play. It should be noted that the synchronous equipment at G has considerably less stored energy than that at R. Because of the lesser stored energy at G, the torque of the fault tends to

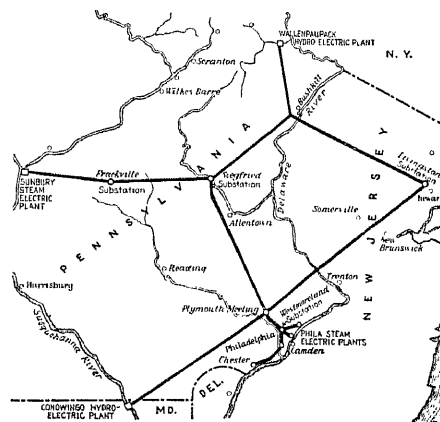


FIG. 8—TERRITORY IN PENNSYLVANIA AND NEW JERSEY TO BE SERVED BY 220-Kv. INTERCONNECTED LINES

slow the generator down faster than the load end of the system R; therefore for the first four-tenths of a second, there is actually a decrease in the angle. Both breakers (fuses) were assumed to clear simultaneously in 0.65 sec. This is exactly simulated on the mechanical system by blowing the fusible links No. 2 and No. 3 in 0.65 sec. It should be noted that the breaker cleared at a point where the angle was considerably less than the final stable angle, with one section of line out so that considerable over-shooting resulted. The dotted section of the calculated curve shows an assumed decrement leading toward the final stable angle. It should be noted also that when the fault was first applied, a slight discrepancy existed between the calculated electrical angle and the actual angle on the mechanical model.

Fig. 7 represents the 10-ohm low-resistance fault on the system shown by Fig. 3-A, with about 140,000 kw. dissipated in the ground circuit. The positive sequence voltage at point of fault was depressed by means of an auxiliary spring, as previously described, to about 73 per cent of normal at the instant the fault was applied. This depression of the position sequence voltage weakened the tie between the two elements so that the angular displacement between the two actually increased during the first part of the fault, which contrasts with Fig. 5 where the positive sequence voltage was fairly well maintained on account of the high resistance in the fault. The circuit breakers (fuses) cleared the line in trouble at both ends in 0.95 seconds. At this time, the arms were traveling toward each other, and there was some overshooting down to the minimum angle occurring at 1.13 sec. before the arms started

traveling apart toward their new positions, with one line out of service.

MECHANICAL MODEL SET-UP OF INTERCONNECTED SYSTEM

Fig. 9 shows the 220-kv. interconnection between the Philadelphia Electric Co., Pennsylvania Power & Light Co., and the Public Service Electric & Gas Co. reduced to a simple form for setting up on the mechanical

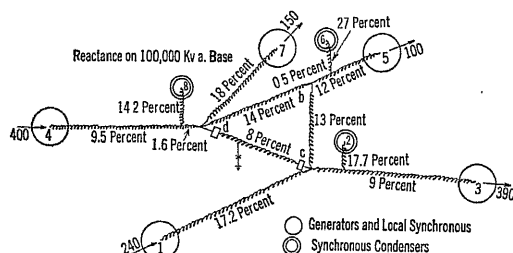


FIG. 9—ARROWS INDICATE THOUSANDS OF KW. ENTERING AND LEAVING NETWORK

Stored Energy of Each Element in Kw-Sec.

1. Conowingo 7.56×10^5
2. Plymouth Meeting 2.2×10^5
3. Phil. Elec. Co., 32.5×10^5
4. P. P. & L. Sunbury 78.0×10^5
5. Public Service Co. 91.0×10^5
6. Livingstone 1.5×10^5
7. Frackville & Siegfried 66 kv. load 39×10^5
8. Siegfried & Frackville Condensers 4.1×10^5

cal model in the same manner as Fig. 3-B was obtained from Fig. 3-A. This figure shows one of the probable future load conditions. The loads supplied local to each generating station are not shown, as they produce very little effect on the phase angular relations of the interconnected system. Only the transmitted power is shown. As previously outlined, the stored energy and reactance of all of the connected generators were included even though under normal conditions these generators may contribute a slight amount of power to the interconnection. During transient disturbances their stored energy and reactance comes into effect and must be considered.

Springs were chosen to represent properly the reactance of each element of the system. The torque required to represent the power generated or the power taken out of the system at each element was determined, and the proper weight to be suspended from each element calculated. In attaching the springs to the arm, allowances were made for the calculated internal voltages. The inertias of the various elements were properly proportioned by hanging equal masses across the elements that required additional inertia. For convenience, these masses were made of tubes that could be loaded with shot. Figs. 10 and 11 show the Fig. 9 system as actually set up on the mechanical model.

With the load and springs properly proportioned, the phase angles between the various component parts of the system assume their proper relationships

automatically. The phase angles shown in Fig. 11 correspond very closely to the calculated values. For the set-up shown, the load conditions were such that practically no power was being transmitted over the section of the triangle B-C in Fig. 9. Fig. 10 shows this to be true. It can readily be seen that a fault on line A-C will be the most severe condition, since the power must be transmitted over the single lines A-B and B-C after the faulty section A-C is tripped out.

Some lines in Fig. 10 utilize two springs in parallel because a single spring of the proper characteristics was not available.

ANALYSIS OF FAULT ON LINE A-B FIG. 9 FROM MOTION PICTURE RECORD OF EQUIVALENT MECHANICAL MODEL

Condition No. 1. A line-to-ground short circuit on line A-C near end A having resistance equal to the reactance to the point of fault was considered. This gave the maximum possible kw. loss in the fault and amounted to about 450,000 kw. for the system shown. (For a complete discussion of the effect of variable ground resistance refer to an article by Mr. S. B.

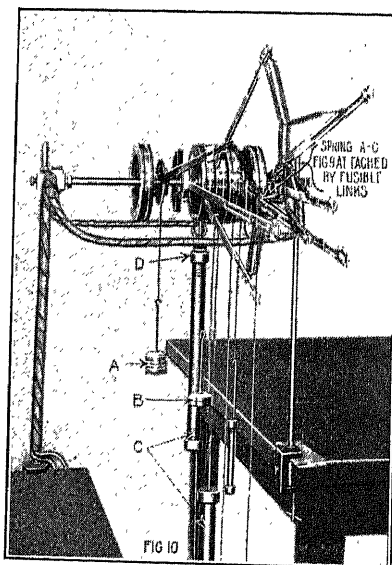


FIG. 10—FOR DIAGRAM OF SYSTEM SEE FIG. 9

- A. Weight producing torque tending to rotate element (1) counter-clockwise, representing 120,000 kw. generated.
- B. Weight producing torque tending to rotate element (3) clockwise, representing 195,000 kw. load. This weight is at greater radius than (A) accounting for the smaller weight
- C. Tubes of equal mass suspended over element (4) to increase its inertia from 32.5 (element alone) to 78 as required by tabulation on Fig. 9
- D. Load weights (partly obscured) representing 200,000 kw. being generated by station (4)

Griscom entitled "Characteristics of Ground Faults on Three-Phase Systems" in the April 1927 issue of the *Electric Journal*. The torque representing this kw. loss in the fault was applied to the spring by means of the very light rotating fault arm shown in Fig. 13a. The function of this arm can be seen more readily from Fig. 1. The spring representing line A-C was attached to the remainder of the system by means of fusible

links arranged to be blown by *CV* relays in order to duplicate the actual opening of the circuit breakers on the system. Fig. 13a shows two successive results at the instant of the application of the fault. The camera shutter did not happen to be open when fuse No. 1 blew, releasing the fault arm, and a spot was placed on the first picture to indicate the blowing of the fuse. The rapid movement of the torque arm is evident, since the pictures are only 0.05 sec. apart.

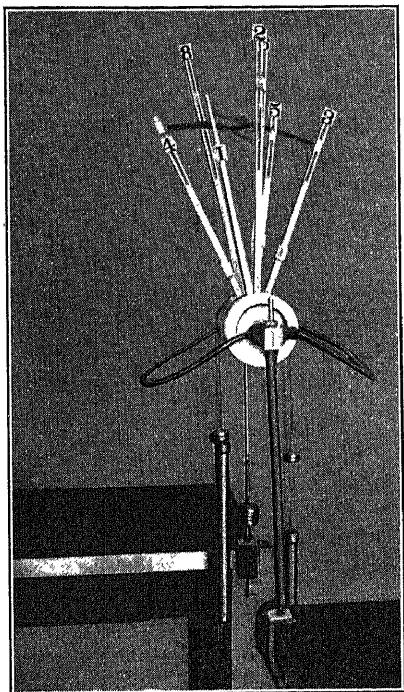


FIG. 11—FRONT VIEW OF FIG. 10

Curve (*d*), Fig. 12, shows the complete angular variation between stations No. 3 and No. 4 and curve (*e*), Fig. 12, shows the corresponding variation between stations No. 1 and No. 3. A cycle counter was included in the field of vision of the motion picture camera as a check on the speed of the film. In Condition No. 1 breakers *A* and *C* cleared the line simultaneously as indicated in Fig. 12. The two successive exposures in Fig. 13b show the released fault arm with the spring *A-C* attached to it swinging clear of the system. In this case the camera shutter did not happen to be open when the fuses representing *A* and *C* cleared.

Fig. 13c shows the crest of the maximum angle between elements 3 and 4. The torque arm with spring *A-B* attached is shown against the stop.

After reaching the maximum angular separation shown in Fig. 12, the stations will oscillate and gradually settle at the new stable position with one line out of service. The present mechanical model does not permit complete rotation and these final oscillations could not be obtained; but they are of no great importance. Fig. 13d shows the final steady-state operating condition with line *A-C* out of service. A considerable increase in the angle between 3 and 4 is evident by comparison with Fig. 13a.

Condition No. 2. The magnitude and location of the fault is identical with Condition No. 1, the only change from Condition No. 1 being in the time of operation of the circuit breakers. By referring to Fig. 12, breaker *A* cleared in 0.68 sec. and breaker *C* in 0.93 sec. When breaker *A* opened, the power taken by the fault had to be transmitted over line *A-B* and *B-C* thereby producing a more rapid increase in the angle between the extreme ends of the system shown by Fig. 12. Fig. 14a shows the conditions at the instant fuse No. 1 cleared, releasing the fault arm. The camera shutter happened to be open when this occurred and the flash can be seen in the picture.

Fig. 14b shows the opening of circuit breaker *A* about 0.68 sec. after the torque arm was released. A dot has been placed on the film to represent the flash of the fuse blowing. The location was obtained from a high-speed film taken simultaneously.

Fig. 14c shows the instant that fuse *C* cleared, allowing the torque arm to swing clear of the system with the spring *A-C* attached to it. The flash has been indicated by a dot located from the high-speed film.

Fig. 14d shows the angular swing due to over-travel after the breaker *C* is cleared. The crest of this swing could not be obtained before element 3 hit the stop,

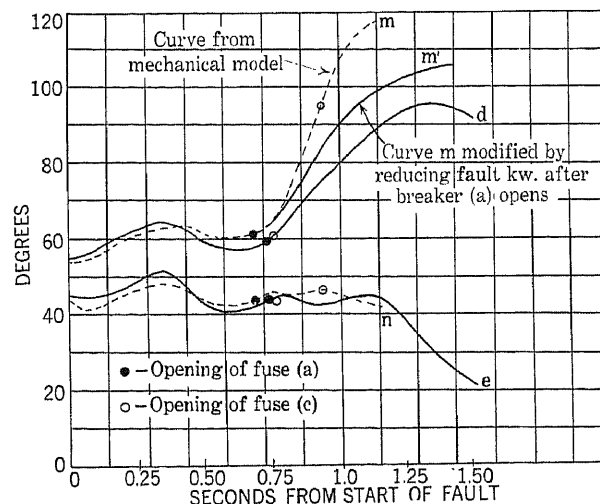


FIG. 12—CONDITION No. 1

d = angle between 3 and 4 (Fig. 9)
e = angle between 1 and 3 (Fig. 9)

CONDITION No. 2

m = angle between 3 and 4 (Fig. 9)
n = angle between 1 and 3 (Fig. 9)

but by comparison with a power-angle curve between stations No. 4 and No. 3 constructed in a manner similar to Fig. 2, it can be ascertained that the system would remain in synchronism. The final steady-state condition with line *A-C* out of service will be the same as Fig. 13d. As indicated by the mechanical model, the effect of opening breaker *C* after breaker *A* is somewhat more severe than will actually be experienced in service, because the reactance to the point of fault is

increased after breaker A opens and a corresponding reduction in the kilowatt loss in the fault should have been made. This reduction can readily be calculated and the slope of curve (m) Fig. 12 modified by calculation. It would also be possible to arrange to release some of the torque when breaker A clears, but this complication can hardly be justified, since the result can be modified readily by calculation. The error due to the torque arm having to swing over sufficiently

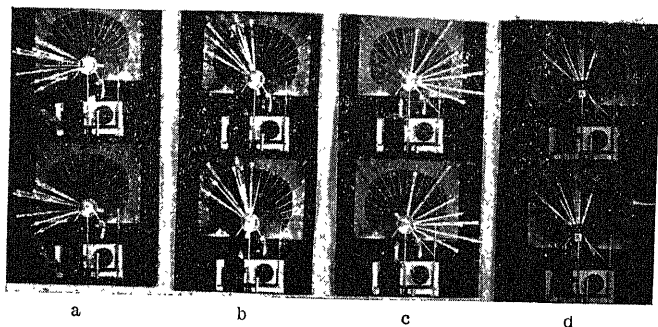


FIG. 13—CONDITION No. 1

EXTRACTS FROM MOTION PICTURES OF 450,000-Kw. FAULT ON SYSTEM SHOWN BY FIG. 9

- a. Conditions at start of fault
 - b. Fuses (a) and (c) clear practically at the same time
 - c. Maximum angular swing between 3 and 4
 - d. Steady state operating condition with line a-c. out of service
- For curves plotted from the motion picture record, see Fig. 12

to take up the initial length of the spring after fuse A clears has been found to be very slight due to the small inertia of the torque arm. If desired, this may easily be taken into account by calculation and modifications made, but the change will be so small that the work cannot be justified except in very special cases.

The close coincidence between the two successive records shown in Fig. 12 should be noted by comparing

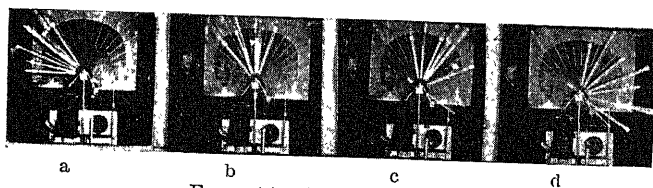


FIG. 14—CONDITION No. 2

EXTRACTS FROM MOTION PICTURES OF 450,000 Kw. FAULTS ON SYSTEM SHOWN BY FIG. 9

- a. Fault applied
 - b. Fuse (a) opens
 - c. Fuse (c) opens
 - d. Maximum angle between 3-4 before element 3 hit the stop
- For curves plotted from the motion picture record, see Fig. 12

the curves for conditions No. 1 and No. 2 prior to the opening of the fuses.

During the foregoing tests, the application of the force representing the short circuit is made at such an angle that the positive sequence voltage at the point of fault was represented by corresponding depression in the spring. The resistance at the point of fault was equal to the reactance in order to obtain the maximum kw. loss in the fault and this resistance limited the

current to such a value that a comparatively small reduction in the positive sequence voltage resulted.

Condition No. 3. This condition represents a line-to-ground fault on line A-C (Fig. 9) near (A) with zero resistance in the fault. The positive sequence voltage at the point of fault will be reduced to about 67 per cent of normal. This was represented by attaching a spring near the end (A) which could be released by the blowing of a fusible link to depress the springs representing line reactance to correspond to 67 per cent voltage without applying any torque (kw.) to the system. For convenience, this spring was attached to the fault arm.

Fig. 15 shows the angular change between the extreme ends of the system plotted against time as taken from the motion picture record. Fig. 16a shows the initial condition a moment after the voltage at (A) was depressed to about 67 per cent of normal. Fig. 16b shows conditions at the instant the fusible link representing breaker C, cleared. The fuse representing breaker A failed to clear and Fig. 16c shows the angular

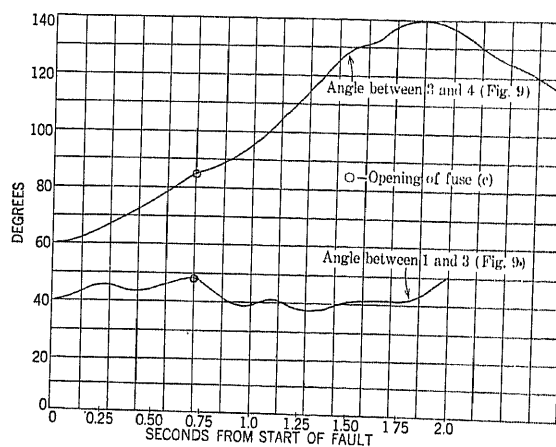


FIG. 15—CONDITION No. 3—ZERO RESISTANCE LINE TO NEUTRAL FAULT NEAR (a) FIG. 9

relation existing when stations No. 3 and No. 4 were at their extreme angular displacement. With the internal voltages in the generators maintained, the system will not pull out of step even though breaker A fails to clear the fault. This may be ascertained from Fig. 15 since the maximum angle of 140 deg. between stations No. 3 and No. 4 did not cause pull-out, and they are swinging back toward a smaller angle. The advantage gained by the use of high-speed excitation, which in so far as practical, maintains the internal voltage in the generators, is evident from an inspection of Fig. 16c.

CONCLUSION

This paper describes the initial attempt to make a quantitative analysis of system transients from motion picture records of a mechanical system having constants proportioned to those of the electrical system. The model was built up of existing equipment and proved to be adequate for the solution of a system problem that

involved too many elements for handling by means of mathematical calculation. The experience gained with this model will prove of value in the development of a model having a greater degree of flexibility for use in analyzing transient conditions on systems with accuracy limitations comparable with the resistance type calculating board now generally used to determine short-circuit conditions for relay and circuit-breaker applications.

It is possible to add a great many refinements to the mechanical model to represent the reactions taking place on systems during transients which have not been taken into account on the device that has been described. In the authors' opinion, it is preferable to use a simple device because results obtained will be comparable in accuracy with the estimates of system conditions to be investigated, since these estimates generally are concerned with conditions that have been projected considerably into the future. Methods of representing a decrease in the internal voltages of the machines and taking into account line resistance as well as reactance have already been described in the May 1926 issue of the *Electric Journal*.

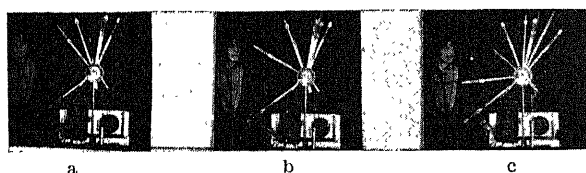


FIG. 16—CONDITION NO. 3

EXTRACTS FROM MOTION PICTURES OF ZERO RESISTANCE LINE TO NEUTRAL FAULT AT (a) FIG. 9

- a. Instant after fault was released, depressing the voltage at (a) to about 66 per cent normal
- b. Instant after fuse (c) opened
- c. Maximum angular swing between 3 and 4

In the transient conditions analyzed in this paper, the load and the kilowatts of input to the generators were assumed to remain constant during the disturbance. Line-to-neutral short circuits seldom cause the positive sequence voltage to drop below 70 per cent of normal and most induction and synchronous motor loads will stay on the line. The transient is over in such a short time that the governors of the generating units do not have time to change greatly the power input. If, however, it is desired to change these factors, it is readily possible by either electrical or mechanical means to change the torque applied to the various elements during the transient. It is also possible to change the torque representing the kilowatts in the fault at the same time that circuit breakers open and reduce the fault current.

The mechanical analogy can be used for the following purposes:

1. Investigation of the adequacy of proposed transmission systems and interconnections for rendering good commercial service in spite of the transient disturbances that are to be expected.

2. Determination of the characteristics that are to be desired in equipment in order to render the required service.

3. Analysis of the most desirable sequence of relay operation. This factor is of great importance in the successful operation of large transmission systems.

4. The mechanical model should be of value in analyzing disturbances on existing systems that have been recorded with automatic oscillographic instruments. The disturbances as recorded can be repeated on the mechanical system set-up and the transients studied by means of slow motion pictures for the benefit of the operating staff.

The results obtained with the initial mechanical model used for quantitative analysis of system disturbances indicate the possibility of building somewhat more flexible mechanical models and the preparation of simple instructions for setting up systems so that the work can be handled by men who have had no previous experience in the calculation of system transients. The mechanical model can be used for quickly analyzing transients on systems having too many elements to be handled mathematically.

In the development of the mechanical model for quantitatively analyzing system transients, the authors have freely consulted the past work of Messrs. Griscom, Wagner, Evans, and Fortescue. The authors wish to express their appreciation of the energetic assistance with the mechanical work rendered by Mr. R. W. MacKay.

LIST OF SYMBOLS USED IN THE FORMULAS

- L = Length of arm on mechanical model representing 100 per cent voltage.
- T = Ounce-inches of torque required to pull out the system with a 10 per cent reactance spring attached to each arm at L inches from the pivot. It is equivalent to the calculated pull-out kilowatts of the identical electrical system.
- $W_1 r_1^2$ = Inertia of mechanical model element in ounce-inches squared. W_1 is weight of element and arm in ounces (not mass) and r_1 is radius of gyration in inches.
- E = Stored energy at synchronous speed in the machines at a station measured in kw-sec.
- $W R^2$ = Inertia of a synchronous machine rotor in pounds-feet squared. W is the weight of rotor in pounds (not mass) and R is radius of gyration in feet.
- Rev. per min. = Revolutions per minute.
- p_1 = kw. per electrical degree of displacement from normal position.

P = Natural period of electrical or mechanical system in seconds.

f = Frequency in cycles per second.

T_1 = Torque in ounce-inches per mechanical degree of displacement from the normal position.

Appendix

DERIVATION OF FORMULAS

Formula (1). Consider a system having 100 per cent internal voltage maintained at each end and a total reactance of X per cent based on M kv-a. Then:

$$\frac{100 \text{ per cent}}{X \text{ per cent}} M = \text{kw. at pull-out.} \quad (12)$$

It is well known that pull-out will occur at a 90-deg. angle between the voltages with a pure reactance tie. The reactive line drop then equals 100 per cent $\sqrt{2}$, which

corresponds to $\frac{100 \text{ per cent } \sqrt{2}}{X \text{ per cent}} M$ kv-a. being trans-

mitted. Since the phase angle is 45 deg. the kw. at pull-out as given by (12) may be obtained by multiply-

ing the kv-a. by $\cos 45 \text{ deg.} = \frac{1}{\sqrt{2}}$.

Formula (2). This formula has been published by others without any derivation being given. For convenience, it will be derived below.

The standard formula for rotational kinetic energy is:

$$\frac{W R^2 \omega^2}{64.4} \text{ ft.-lb.} \quad \begin{array}{l} (W \text{ is weight of rotor in pounds}) \\ (R \text{ is radius of gyration in feet}) \\ (\omega \text{ is angular velocity in radians per second}). \end{array} \quad (13)$$

Substitute in (13) for ω its value in terms of (rev. per min.):

$$\omega = 2 \pi \frac{(\text{rev. per min.})}{60} = \frac{\pi (\text{rev. per min.})}{30} \text{ radians per second.} \quad (14)$$

Multiplying by the factor $13,560 \times 10^{-7}$ to convert ft.-lb. to kw. Second formula (2) is obtained.

$$(2) E = \frac{2.3 (W R^2) (\text{rev. per min.})^2}{10^7} \text{ kw.-sec.}$$

Formula (3). Conversion of electrical system stored energy (E -kw.-sec.) into equivalent $W_1 r_1^2$ (ounce-inches squared) on the mechanical model.

In the paper under "Conversion of the Electrical System into Equivalent Mechanical System" the method of obtaining the proportionality factor between kilowatts in the electrical system and torque in ounce-inches on the mechanical model was described. Consider an element of the electrical system having E kw.-sec. of stored energy at synchronous speed. If a load $\text{kw.}_{po} = T$ oz.-in. on the mechanical model (kw._{po} = pull-out kw.) is taken from the synchronous machines

constituting E , they will slow down a total of ϕ_1 electrical degrees if no additional power is supplied.

$$\phi_1 = \frac{5400 (\text{kw.}_{po})}{E} t_1^2 \text{ elec. deg.} \quad (15)$$

This formula will be derived later in the appendix.

The torque T applied to the mechanical system should cause a movement of ϕ_1 mechanical degrees in t_1 seconds if the $W_1 r_1^2$ of the model is properly proportioned to E of the electrical system. For the mechanical system:

$$\phi_1 = \frac{11,085 T}{W_1 r_1^2} t_1^2 \text{ mechanical degrees.} \quad (16)$$

This formula will be derived later in the appendix.

Equating (15) and (16) and canceling out t_1^2 :

$$W_1 r_1^2 = \frac{E \times T \times 2.05}{\text{kw.}_{po}} \text{ oz.-in. squared.} \quad (17)$$

In the example shown in the paper $\text{kw.}_{po} = 10^6$ or

$$(3) W_1 r_1^2 = \frac{E \times T \times 2.05}{10^6} \text{ oz.-in. squared.}$$

In the foregoing, E has been assumed to remain constant during changes of speed. This has been found to be sufficiently accurate for stability calculations because the transients last such a short time that the departure from synchronous speed is very small.

Formula (15). Used in deriving formula (3).

The torque (T_{36} lb.-ft.) that will change the angular velocity of a body having an inertia of $W R^2$ (lb.-ft. squared) from ω_1 to ω_2 radians per second in time t seconds as given by the standard formula is:

$$T_{36} = \frac{W R^2 (\omega_1 - \omega_2)}{32.2 t} \text{ lb.-ft.} \quad (18)$$

In deriving formula (16) it is convenient to consider all machines as running at 3600 rev. per min. and convert the $W R^2$ and electrical torque to this base, since the mechanical and electrical degrees are the same at this speed. From formula (2).

$$E = \frac{2.3 (W R^2)_{36} \times 3600^2}{10^7} \text{ kw.-sec.} \quad (19)$$

or $(W R^2) = 0.335 E \text{ lb.-ft. squared at 3600 rev. per min. to have stored energy of } E \text{ kw.-sec.} \quad (20)$

The torque (T_{36} ft.-lb.) at 3600 rev. per min. produced by (kw._{po}) is:

$$\frac{\text{kw.}_{po}}{0.746} = \frac{2 \times 3600 \times T_{36}}{33000} \quad (21)$$

$$\text{or } T_{36} = 1.95 (\text{kw.}_{po}) \text{ lb.-ft.} \quad (22)$$

The angular velocities ω_1 and ω_2 in radians per second may be converted to degrees per second as follows:

$$\omega_1 = \frac{\omega_{10}}{57.3} \quad (23) \quad \omega_2 = \frac{\omega_{20}}{57.3} \quad (24)$$

ω_{10} and ω_{20} are in either electrical degrees per second or mechanical degrees per second on the 3600 rev. per min. base previously referred to.

Substituting (20), (22), (23), and (24) in formula (18):

$$(kw_{po}) = \frac{E (\omega_{10} - \omega_{20})}{10,800 t} \quad (25)$$

The angular change ϕ_1 (elec. deg.) in time t_1 , may be determined as follows:

$$\phi_1 = \int_0^{t_1} (\omega_{10} - \omega_{20}) dt = \int_0^{t_1} \frac{10,800 (kw_{po})}{E} t dt \quad (26)$$

$$\text{or} \quad \phi_1 = \frac{5400 (kw_{po}) t_1^2}{E} \text{ elec. deg.} \quad (15)$$

Formula (16). Used in deriving formula (3). Starting from formula (18) as a basis substitute for T_{36} (ft.-lbs.) its equivalent torque T (in.-oz.)

$$T_{36} = \frac{T}{16 \times 12} = \frac{T}{192} \quad (27)$$

The $W R^2$ (lb.-ft. squared) may be converted into $W_1 r_1^2$ (oz.-in. squared) as follows:

$$W R^2 = \frac{W_1 r_1^2}{16 \times 12 \times 12} = \frac{W_1 r_1^2}{2304} \quad (28)$$

Substituting (23), (24), (27), and (28) in formula (18):

$$T = \frac{W_1 r_1^2 (\omega_{10} - \omega_{20})}{22,170 t} \text{ oz.-in.} \quad (28)$$

(ω_{10} and ω_{20} in mech. deg.)

The angular change, ϕ_1 (deg.) in time t_1 may be determined as follows:

$$\phi_1 = \int_0^{t_1} (\omega_{10} - \omega_{20}) dt = \int_0^{t_1} \frac{22,170 T}{W_1 r_1^2} dt \quad (29)$$

$$\text{or} \quad \phi_1 = \frac{11,085 T}{W_1 r_1^2} t_1^2 \text{ mech. deg.} \quad (16)$$

Discussion

B. Van Ness: The eastern 220-kv. interconnection presents an unusually interesting problem from the stability standpoint because of the large number of different factors involved. Of particular interest is the proposed parallel operation of existing stations equipped with normal excitation and new stations equipped with quick response and even superexcitation.

In this connection I should like to ask the authors of the papers if their studies have indicated any need for the installation of quick-response excitation in the existing stations in order that the speed of response be more nearly uniform throughout the system; also if voltage fluctuations and surges are to be expected from wattless readjustment caused by the difference in speeds of excitation response.

L. G. Smith: There are several points that I am not sure the authors of the paper have considered in designing the mechanism for calculating system stability. One is the effect of steam generating stations in that the steam governors may start to function during the period of oscillation during the transient condition and thus superimpose their effect upon the natural oscillation

that may occur. Another point is the time lag of relays which may have some effect upon system stability. The energy supplied to the normal short circuit is almost entirely wattless. Under these conditions we might actually have an unloading effect on the generators and a tendency for them to speed up. This may have some effect upon the stability of the system. Can this effect be determined?

The growth of interconnections has introduced the subject of stability in many of our power systems. In the East it is more or less a practise to interconnect systems through solid interconnections, attempting to hold all parts of the system in synchronism. I understand that there is a tendency on the Pacific Coast to adopt a system of loose linkages, that is, to tie the system together loosely so that various parts will separate in case of trouble. Perhaps Mr. Baum can give some thoughts on this subject.

Quick response excitation would function to hold the voltage up during a short circuit. Suppose that the trouble is cleared and the short circuit removed from the system after the quick-response excitation of the condensers has functioned. Is the system designed to reduce the voltage quickly in order to prevent an over-voltage on the synchronous condensers, which may cause an insulation failure on some part of the system?

F. G. Baum: No electrical system can be operated without means for removing defective sections. The solution has been the bother of the electrical engineer for many years.

Thirty years ago generators were often advertised as being very good because they had very large reactance. One manufacturer made it a point that you could actually short circuit his machine for hours at full voltage and it would do no harm. All that was good for the time, but it just happens that that generator manufacturer is not in business now; perhaps he had the wrong idea.

There was a reason, then, for having high generator reactance, because 30 years ago we had no oil switches whatever when we started operating on 40,000 volts, nothing but fuses and air switches. The average interruption at that time was some 25 to 30 min. We made up our minds that this had to be remedied, so we made up some improvised oil switches. With the subsequent improvements in switches and relays, results have been accomplished that are really wonderful. Now we are striving to maintain the generated voltage by high-speed excitation and other means.

That matter of cutting the system into parts, which has been mentioned by one of the speakers, was tried 25 or 30 years ago when we tied the northern end of the Pacific Coast system to the south switch and a man stood at that switch day and night and separated it by pulling a lever. Of course operations are now going forward in an improved way. Some 50 different power plants feeding into the San Francisco Bay District are so connected that in case of trouble they can be divided into parts.

I should like to call attention to the synchronous condenser value. It has, first, a value in increasing the power capacity of a transmission line. That is, a 220-kv. transmission line has a normal capacity, as I call it, of transmitting power of about 120,000 kw. at a constant voltage. That is, when that amount of power is being transmitted over a transmission line the charging current is just such as to give a uniform voltage over the transmission line, which could theoretically go around the world and end up with the same voltage you start with.

The charging current of a transmission line is some 25,000 kv-a. per hundred miles. It used to be thought that that was a liability, but if you match that 25,000 charging kv-a. with 25,000 to 30,000 of synchronous-condenser kv-a. you make that charging current an asset.

The second advantage of the condenser is that it increases the stability of the transmission system.

The third value of the condenser is not generally recognized. I will refer to the Pacific Gas & Electric Company system, com-

prising more than 50 different power plants feeding a general receiver area. Before we had a main synchronous-condenser control station it was necessary for the load dispatcher to telephone to 50 different operators as to how much kv-a. they should put into the system at different times of the day. And it became almost impossible to handle that job because one plant would try to slip the charging kv-a. onto the other fellow. At the present time there is 80,000 kv-a. in the central system condenser station feeding into it, and the load dispatcher tells the power stations what kilowatts he wants delivered and the voltage regulation is all done by the one condenser station. The load dispatcher told me a few years ago that the old system would be practically impossible to operate, but now he has one station which can control the voltage of the whole system as he desires. Now the instructions are simpler and the whole system operates much better and probably a very large system like that would be impossible to operate without synchronous condensers, if they were of value, for no other reason than to simplify the method of operation of voltage regulation.

F. C. Harker: The ultimate aim of any power system is to maintain continuity of service, and these recent modifications are for the purpose of improving the service record. Mr. Baum has mentioned that you have to remove the line or section of the circuit in trouble off the system just as quickly as possible. If you do that within a tenth of a second, or within that order of time, your general problem of operation and maintaining service will be very much simplified.

One of the problems that resulted from the study of system conditions was the method of calculation. These are more involved, sometimes, than the systems themselves and Mr. Bergvall is to be commended on the use he has made of the simple, mechanical model, in simplifying the analysis of the more complicated systems. The simple model has done more to visualize to the operating man the conditions that exist in his system than any other method; far more than could be done by any amount of discussion.

At the last Pacific Coast Convention the operating men, in connection with the manufacturers, presented a paper showing two years of operation on the Edison System. If we had similar data on other systems we could soon set up a definite measuring stick to help tell us where we are going and where we would land on systems of two and three times present capacity. It won't be many years before our systems are going to double and quadruple and when that time comes we are not sure whether the present system of operation will be desirable and effective, or whether we shall have a modified system, which may be either a combination of the present with a new, or perhaps an entirely different one. I think the operating engineers should give more thought to that phase of the matter because it does offer a problem of considerable importance.

A. E. Bauhan: Not so many years ago the question of stability was practically unrecognized as a cause of major system troubles. In my experience with the Baltimore systems some years ago, we had numerous cases where ordinary 13,000-volt feeder short circuits were given the blame for major outages. These short circuits in themselves were really minor troubles and should have cleared by relay action without serious interruption of service, but for reasons not clearly understood at the time, general disruption of the whole system with loss of interstation ties and main transmission followed. It was later recognized that with the system connections then in use there was a condition of transient instability which was the real cause of the major trouble. Since then more recognition has been given to this matter generally and with better understanding of the conditions influencing stability under short-circuit conditions, system operation is being improved.

When the particular interconnection referred to in this paper was conceived a few years ago the question was raised as to what the stability limit would be, and the figure mentioned was

quite different from the one that has recently been determined. As time went on, and new calculations were made, lower and lower limits were reported. Later the figures from various sources became consistent with each other and there was more assurance that the approximately correct answer had been reached. This is significant of the progress which has been made in determining maximum power flow and the mechanical analog which has been explained here today has had much to do with clarifying this problem.

Fortunately, with regard to the Pennsylvania-New Jersey interconnections, distances are short and the question of stability did not affect the economic feasibility of the project, the stability limits being considerably higher than the loads which were necessary to justify the interconnection. However, on long-distance transmission of large amounts of power, the stability limit affects the number of circuits and the amount of synchronous-condenser capacity and therefore the cost of a major element of the delivered power cost. Its accurate prediction in such cases is of great importance in determining the economy of the project.

With regard to the question as to the effect of voltage dips in one part of the system being transmitted to another part of the system, my view is that we will have some trouble from that source. There will doubtless be a larger number of voltage dips on the individual systems than would have occurred without interconnection. However, I do not regard such voltage disturbances as being important. To the lighting customers they are mere flickers of the lights. To the power customers whose switches are equipped with instantaneous low-voltage releases, the more serious voltage disturbances will cause interruptions. In those applications where continuity is important the instantaneous low-voltage release has no place in any event and the remedy lies in seeing that all such applications have time delays on any necessary low-voltage releases.

P. H. Robinson: The Westinghouse Electric & Manufacturing Company has conducted extensive tests and development work on the regulating equipment for the condensers being supplied for the Westmoreland Substation. In order to handle the heavy field currents necessary to build up the reactive kv-a. at a high rate of speed, special regulator contactors were developed and will be used in connection with a suitable system of relays for control.

The exciters are of special design, having a laminated frame and comparatively few field turns. Laminating the frame was found necessary in order to reduce the retarding effect of eddy currents on the building up of the flux in the exciter. If a solid frame were used it would not be possible to obtain such an extremely high rate of building up of the exciter voltage.

While we were conducting tests on a synchronous condenser, a phenomenon occurred which was quite interesting. It was found for the particular machine under test that three or four times normal field current would cause hunting and finally make the condenser drop out of synchronism and stop suddenly. This heavy field current made the natural period of the machine identical to a natural oscillation existing in the supply system.

It might be well to investigate the possibility of such an occurrence on an actual system.

A. F. Bang: In underground systems in practically all large cities, nowadays, it is recognized as good practise to have reactance coils at both ends of a feeder. These coils not only limit the current that the switches have to take care of, but also, and this is the main point, keep up the voltage on the station busses between which the fault is located.

Now, when almost everybody realizes that this is the right thing to do in city systems, why is it almost standard practise to parallel on the high-tension side when it comes to transmission-line systems? I, for one, cannot see the logic of the situation. By not paralleling the transformers on the high-tension side, the transformers themselves will act as reactance coils to keep up the voltage on the generating station busses. A system of this kind

has been used successfully for many years on the Pennsylvania Water & Power Company's 70,000-volt lines and we believe the system has many advantages, particularly for relatively short lines.

Raymond Bailey: The studies which have been made on the Coast where 220-kv. systems have been in operation for some time, and also those made in the East largely by engineers of the manufacturing companies, have proved very helpful. Considerable progress certainly has been made, but I believe we still have much to learn about stability of operation, and it is expected that in the future we will profit not only by further analytical studies that will be carried along, but also from actual experience of operation.

It seems to me to be of extreme importance, particularly in a system in which large blocks of power are transferred over great distances, to isolate faulty sections of the system with minimum time delay in order to prevent unstable operation. The development of circuit breakers that open the circuit more quickly or development of relay protective schemes that do not depend upon a time delay in their operation may lead to reduction in the length of time required to clear faults from systems.

Our efforts in designing the relay protective system for the Conowingo project have been to secure means for isolating faulty sections as quickly as possible under all conditions. This condition, along with the high-speed excitation on the Conowingo generators and on the condensers at the receiving end, we believe will do much to insure stability of operation.

R. C. Bergvall and P. H. Robinson: Mr. Smith has brought up the question of governor action during system transients. The transients produced by severe short circuits are of such brief duration that normally the governors will not appreciably change the input to the prime movers until after the disturbance has been cleared. A number of cases is known where disturbances and the accompanying switching operations have set up severe hunting between interconnected stations whose governors were not properly adjusted. The solution of this problem is proper governor adjustment and is beyond the scope of the mechanical model analysis. Wattless short circuits that are severe enough to cause the generators to speed up indicate that the short circuits have been of the 3-phase type, entirely removing the tie between the generators and the load and the speeding up indicates that loss of synchronism has occurred. The time lag in the relays has been added to the circuit breaker operating time in making the analysis.

Mr. Bang mentioned using reactors in transmission lines similar to the present practise which has proved beneficial on lower-voltage circuits. Generally, there are only two or three high-voltage transmission lines tying together two systems. With reactors placed in these lines the loss of one circuit greatly increases the amount of reactance through which synchronism must be maintained, and the reactors even though they cushion the initial short circuit will be detrimental due to decreasing the strength of the tie line. On lower-voltage circuits the reactors are generally used in feeders that are not depended upon for furnishing synchronizing power and the reactors are beneficial in reducing the severity of the short circuit.

Mr. Bang brought up the question of using transformers as a part of the line to serve as reactors and limit the short circuits. There are undoubtedly cases where such practise would be of value but it is impossible to give general conclusions as each case would have to be considered individually.

The use of quick-response excitation systems on the important generating stations in an interconnected system will be of great value in maintaining stability during transient disturbances.

D. M. Jones: With the mechanical device described by Messrs. Bergvall and Robinson it would appear that once a given system is reduced to an approximate mechanical counterpart it would be very easy to obtain data on the relative effect of variation in certain basic factors; also, in a sense, the analog is

free from the small cumulative error inherent in step-by-step calculation processes. Finally, it has a certain visual quality which is of value in providing general images of what takes place on a system during disturbances.

The analog in turn has its inherent difficulties. It is evident that it is devoid of large amounts of friction. It might at first be thought that such friction as might exist would be very closely akin to the damping that actually occurs in the system. Two comments on that might be of interest.

Of course to the small degree that there is any friction it is not an exact counterpart of the damping, as friction is practically a constant force and damping is a force which should vary with the rate of motion of the levers.

The other thing that may be of more interest is that it is a matter of both experience and test that certain system conditions, especially those including high-resistance lines, result in a considerably reduced or even at times an actual negative damping. This condition not only causes mechanical friction to be at basic variance with the true requirements, but also suggests a point of departure between the analog and the facts.

The presence of appreciable series system resistance also results in a condition which is not rigidly represented by the symmetrical simplicity of a generator lever and a load lever cross-tied with a spring with the resulting maximum mechanical torque angle of 90 deg.; for such resistance tends to increase the real maximum load angle for the generator and at the same time to decrease it for the load to values departing from the basic value above mentioned.

Also, to the degree that salient-pole machines are present on a system, a condition arises which does not coincide with that assumption of a sine wave torque-angle curve for all machines, on which the analog is based, because salient-pole machine torque-angle curves are never true sine curves and may depart appreciably from them as has been brought out in *Synchronous Machines I*, by R. E. Doherty and C. A. Nickle, (see A. I. E. E. TRANS., Vol. XLV, 1926, p. 942).

Again, although mechanical simplicity suggests the representation of short-circuit disturbances by a fixed lever length to which is applied a fixed force, which is the equivalent of a constant voltage at the short, and a fixed loss therein, the actual voltage and loss are never constant throughout the duration of the short circuit and often vary considerably.

These comments in suggesting certain limitations in the mechanical analog are not offered in condemnation of this most interesting device, but rather to point out the probability that there will be certain system conditions where the results obtained from it will be satisfactory and others where the errors may be unduly large, and to express the hope that work on it may continue to the end that the connection between the type of system condition and the resulting error may be thoroughly established.

Mr. Smith mentioned overvoltage with regard to excessive excitation applied to synchronous condensers. He has mentioned that very justly. That is one of the distinct limitations of excitation to abnormal degrees. In the condenser on the Conowingo system this is taken care of by the regulator, and of course that maximum voltage on the exciter disappears very quickly, so that the amount of excitation that has to be reduced is not a thousand volts but that equivalent refers to the double field current, and as has been pointed out you are up against a condition which is influenced by two factors: how quick your equipment is in controlling the overvoltage, and the degree of overvoltage which the equipment itself would produce on the actual system.

I wish to substantiate the remarks made by Mr. Bergvall about the lightning-arrester question. It was felt that the maximum voltage which the lightning arrester would allow was considerably lower than the voltage which might occur on the line and therefore that its installation was justifiable.

I might make one minor comment with regard to a remark

that Mr. Bang made. If, by use of reactance in any position you can materially reduce the disturbance without materially reducing the capacity of the synchronizing path you have done a very good thing. Now on our network it is probable that when you put in reactors you have not materially reduced the synchronizing path in general, as the thing is a pretty widespread network, while the reactor is very effective in reducing the short circuit. Furthermore if you had any system and short circuits of such a nature that you could control the magnitude by putting in reactance in such a way that you didn't influence the synchronizing path, it would be of advantage. That might be one way of obtaining certain benefits in stability. You could limit the path of the fault current probably without limiting the path of the power flow, and that would be of advantage.

R. C. Bergvall and P. H. Robinson: With reference to Mr. Jones' discussion, we recognize that friction is not an exact counterpart of damping, but both of these forces are so small that in an analysis of this type they can be neglected. In most systems of sufficient magnitude to warrant a stability study no appreciable error is introduced by neglecting the series resistance as it amounts only to 1/10 or 1/12 of the reactance. It is true that salient-pole synchronous machines deviate somewhat from the sine-wave torque-angle curve for steady-state conditions, but during transients we are concerned with the characteristics

of machines having the internal flux linkages maintained by means of quick-response excitation and the torque-angle characteristics approach the sine function. The demagnetizing action of the fault current in the armature of the synchronous machine is counteracted by the increase of excitation brought about by rapidly increasing the voltage applied to the field of the synchronous machine.

It is recognized that the application of a constant force to represent a fault is not exactly correct as pointed out in the paper. We must consider, however, that for the analysis of a complicated problem of this nature it is necessary to make certain assumptions which although not rigidly true, simplify the problem and do not affect the results to such a marked degree as to cause them to be incorrect in the general case. There is no method of predetermining the variation of the loss in a fault as there are so many factors involved that it would be impossible to exactly duplicate a condition. Any given or assumed fault condition can be analyzed and its effect upon the system determined.

The stability study has indicated the desirability of using quick-response excitation systems on the large generating units to maintain internal voltage under fault conditions. The value of such a scheme has been recognized for some years but only recently has been put into practise.

Squirrel-Cage Rotors with Split Resistance Rings

BY HANS WEICHSEL¹

Fellow, A. I. E. E.

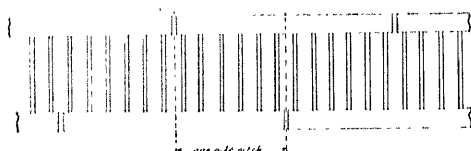
Synopsis.—The characteristics of a squirrel-cage induction motor are investigated when the resistance rings are provided with cuts 360 electrical deg. apart and the cuts in the front ring are displaced against those in the back ring by 180 electrical deg.

A theoretical investigation is given, which leads to the conclusion that splitting the rings results in an equivalent ring resistance which varies with double-slip frequency in the ratio of one to three; and the average ring resistance is twice what it was before the rings were cut.

The variable rotor resistance effects a periodic fluctuation of the line current and rotor speed. The fluctuations have double-slip frequency. The theoretical conclusions are checked by tests and oscillograms. Test results show that the splitting of the rings is followed by increased rotor leakage, which results in a starting torque smaller than that corresponding to the increased resistance and original leakage.

* * * * *

WHEN the starting torque of a squirrel-cage induction motor is not sufficiently high, the remedy often suggested is to divide each resistance ring by aid of saw-cuts into half as many sections as there are poles, the saw-cuts in the front ring being displaced against those in the back ring by an angle corresponding to one-pole pitch (180 deg.). A developed view of a four-pole squirrel-cage arranged in this manner is diagrammatically represented in Fig. 1.²



The squirrel-cage rotor with its rings modified in this manner offers a resistance higher than an identical squirrel-cage with uncut rings. Below, it will be determined how much that part of the squirrel-cage rotor resistance which is due to the rings only is increased by cutting the rings. It will be found that a squirrel-cage with cut rings offers an *average* ring resistance equal to twice the resistance of the original uncut rings. A proof for this is as follows:

First, it is necessary to consider the current distributions and losses which take place in a squirrel-cage of the standard construction, using solid end rings, or so called resistance rings. Fig. 2 represents the current distribution in a two-pole squirrel-cage rotor with solid rings. In drawing the current distribution, it has been assumed that the ampere conductors on the stator follow a sine-law distribution in space. Strictly speaking, such a distribution exists only when the stator has an infinite number of phases and slots; but even for a finite number of phases and slots the above distribution is approached. For a sine-shaped stator ampere-

conductor distribution, the rotor-current distribution must also follow the sine law. The rotor ampere-conductor distribution rotates in respect to a fixed point on the rotor with a speed corresponding to slip frequency. The shape of the distribution remains unaltered. In other words, Fig. 2 can be considered as showing the current distribution in the squirrel-cage at any moment. This distribution remains independent of time.

If the distance between two adjacent rotor bars is δ electrical deg., and the rotor has an even number of bars per pole, the current in the different bars has the following values:

$$\text{Current in bar } I_1 = I \times \sin \frac{\delta}{2}$$

$$\text{Current in bar } I_2 = I \times \sin \delta + \frac{\delta}{2}$$

$$\text{Current in bar } I_3 = I \times \sin 2\delta + \frac{\delta}{2} \text{ etc.}$$

These equations are vectorially represented in Fig. 3.

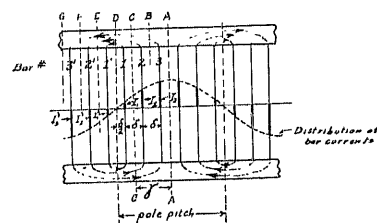


FIG. 2

The vectors 1-2, 2-3, 3-4, 4-5 are alike and are equal to I . (i. e., the maximum current which any of the bars can carry), and are displaced against each other by the angle δ . All these vectors form a polygon, the circumference of which approaches the value $2Z \times I$, where Z is the number of squirrel-cage bars for one pole. The radius of a circle circumscribing this polygon is, therefore, given by the equation:

$$r = \frac{2Z\bar{I}}{2\pi} = \frac{Z\bar{I}}{\pi} \quad (1)$$

1. Consulting Engineer, Wagner Electric Corp., St. Louis, Mo.

2. This scheme was originally suggested by Ziegler, see Electric Motors, by H. M. Hobart, p. 314.

Presented at the A. I. E. E. Regional Meeting, St. Louis, Mo., March 7-9, 1928.

As shown above the current in bar 1 is $\bar{I} \sin \frac{\delta}{2}$.

The current in bar 2 is $I \sin \left(\delta + \frac{\delta}{2} \right)$, and the

current in bar 3 is $\bar{I} \sin \left(2\delta + \frac{\delta}{2} \right)$. From Fig. 3

it will be seen that these current values are represented by the lines 2-7, 3-8, 4-9, etc. In other words the projection of the lines 1-2, 2-3, 3-4, 4-5, etc., on the horizontal diameter 0-1 represents the bar currents $I-1$, $I-2$, $I-3$, etc.

From the distribution of the bar currents, as given in Fig. 2, the distribution of currents in the ring can be derived.

For the purpose of symmetry (see Fig. 2), it is permissible to say the current $I-1$ and the current $I-1'$ form one circuit. In the same manner the current $I-2$ in bar 2 completes its circuit with current $I-2'$ in bar 2', etc. Consequently, the section A of the ring does not carry any currents at all; while the section B

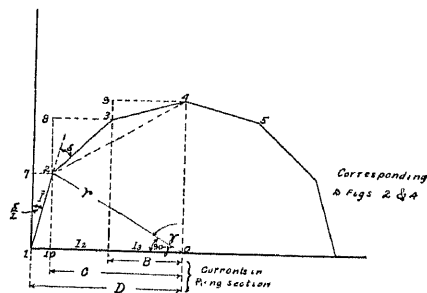


FIG. 3

carries a current $I-3$; the section C carries the current $I-3$ plus $I-2$; section D carries current $I-1$ plus $I-2$ plus $I-3$. Therefore, the ring current is a maximum where the bar current is zero, and the ring current is zero where the bar current is a maximum. Considering for a moment the ring section C , which carries bar current $I-3$ plus $I-2$, we see from Fig. 3 that the current in this section is equivalent to the projection of the chord 2-4 on the base line 0-1. But this can also be considered as the projection of the radius $r = 0-2$ on the base line 0-10. Thus the current in ring section C can be expressed as

$$I_c = r \cos (90 - \gamma) = r \sin \gamma \quad (2)$$

where γ is the angle the radius 0-2 forms with the radius 0-4, which is identical to saying the angle γ is the distance, measured in electrical deg., from the center of section C to the center of section A . By equation (2) it is demonstrated that the current distribution in the rings follows a sine curve, being zero at the point A . As seen, previously, the current distribution in the bars follows a sine curve, being zero at

the point D . Points D and A are 90 deg. displaced from each other. Therefore, if both curves refer to the same starting point, one of the curves is a sine curve and the other is a cosine curve. Substituting in equation (2) the value for r from equation (1), it follows:

$$I_\gamma = \frac{Z \bar{I}}{\pi} \sin \gamma \quad (3)$$

which expresses the ring current at any section γ as function of the maximum bar current \bar{I} . The loss due to the ring current is at any point proportional to the square of the current. Consequently the loss at any point is obtained by squaring equation (3) and multiplying it with a coefficient k , which takes care of the resistance of the ring section under consideration. The loss at any point is, therefore:

$$\frac{Z^2 \bar{I}^2}{\pi^2} \sin^2 r \times k \quad (4)$$

The total ring loss is the integral of equation (4) and is given by equation:

$$\text{Loss in one ring per pole} = 2 \int_{r=0}^{r=90} \frac{Z^2 \bar{I}^2}{\pi^2} \sin^2 r \, k \, dr \quad (5)$$

k = resistance of a ring portion corresponding to a unit angle. Therefore, if k is the resistance of one ring spanning an arc corresponding to one pole pair (2π),

$$\text{we obtain:} \quad k = \frac{R}{2\pi} \quad (6)$$

The solution of the integral part of equation (5) is:

$$2 \int_{r=0}^{r=90} \sin^2 r = 2 \left(\frac{1}{2} r - \frac{1}{4} \sin 2r \right) \Big|_0^{90} = \frac{\pi}{2} \quad (7)$$

Consequently the losses in one ring per pole

$$= \frac{\pi}{2} \cdot k \frac{Z^2 \bar{I}^2}{\pi^2}$$

Substituting $k = \frac{R}{2\pi}$ from equation (6), it follows:

losses in one ring per pole =

$$\frac{R}{2\pi} \cdot \frac{\pi}{2} \cdot \frac{Z^2 \bar{I}^2}{\pi^2} = \frac{R Z^2 \bar{I}^2}{4\pi^2}$$

and the losses per pole pair and both rings equal:

$$\frac{R Z^2 \bar{I}^2}{\pi^2} \text{ if } \bar{I} = \hat{I} \sqrt{2} \quad (8)$$

The losses in both rings per pole pair equal:

$$\frac{R Z^2 \hat{I}^2 2}{\pi^2} \quad (9)$$

R = resistance of ring spanning two-pole pitches

Z = number of squirrel-cage conductors per pole

\bar{I} = effective rotor-bar current per pole

The laws established so far are well-known and refer to the current distribution and losses in the bars and rings of a squirrel-cage whose rings are solid, (Fig. 2). The relations are not quite as simple for a squirrel-cage with slotted endings (Fig. 1).

Figs. 4 and 6 show a two-pole squirrel-cage winding with end rings split in the manner described. It has been shown above that the current distribution in the

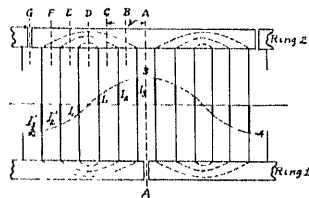


FIG. 4

squirrel-cage bars must follow a sine law as long as the current distribution in the stator follows the sine law. The current distribution in the bars is given by the sine curve 2-3 4 (Fig. 4) for the moment when the rotor bar currents are so located that the maximum bar current coincides with the slot A in the ring 1. This distribution is identical to that shown in Fig. 2. It is evident that the ring currents in Fig. 4 must be distributed

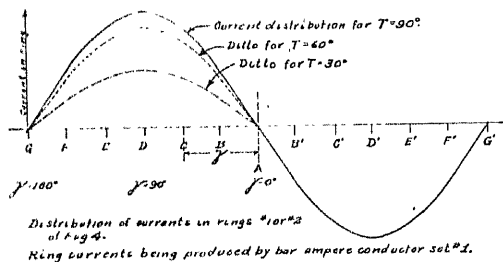


FIG. 5

butted as shown, which when plotted in a coordinate system as a function of space gives Fig. 5.

Conditions change materially if the moment is considered when the sine-shape distribution of the bar currents is so located that the bar carrying no current coincides with the cut A in ring 1, as shown in Fig. 6. With the bar current in this distribution, it is no longer possible that the current $I-1'$ and $I-1'$ close symmetrically in rings 1 and 2, as found for Fig. 4. The only symmetrical ring distribution possible with the symmetrical bar distribution is that given in Fig. 6, i. e., section F in ring 2 must carry the bar current I_1 . The section E carries bar current I_2 plus I_1 ; section D carries I_1 plus I_2 plus I_3 . Section C carries I_1 plus I_2 plus I_3 plus I_4 . Section B carries I_1 plus I_2 plus I_3 plus I_4 plus I_5 , and, finally, section A carries the sum of all bar currents of one pole, i. e., $I_1 + I_2 + I_3 + I_4 + I_5 + I_6$.

A more general expression for the currents in the ring

section with a bar-current distribution (Fig. 6) is obtainable as follows:

Vectors 1-2, 2-3, 3-4, 4-5, 5-6, etc. (Fig. 7) represent the maximum current in any of the rotor bars. Each vector is drawn against its preceding vector under an angle δ equal to the displacement of the bars against each other. The vector 1-2 is shown displaced against the vertical 1-7 by an angle $\frac{\delta}{2}$. The current I_1 in

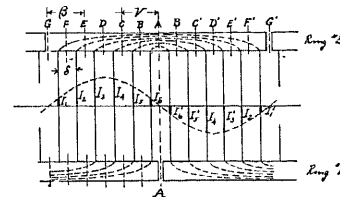


FIG. 6

In other words the bar currents are the projections of the vectors 1-2, 2-3, etc., on the base line 0-1'. So far the diagram is identical to Fig. 3. The current passing through the ring section F, as shown above, is equal to the bar current I_2 . Consequently, it is given by the length 2-7 or 1-10 (Fig. 7), which is the projection of the vector 1-2 on the base line. The current through the ring section E is the sum of bar current I_1 and I_2 . It is consequently given by the length 1-11, which is the projection of the vectors 1-2 and 2-3.

If the currents in the different sections, A, B, C, D, E, and F, are plotted as function of their space location, a current distribution in the ring is obtained as shown in Fig. 8. A glance at Figs. 6, 7, and 8 shows the

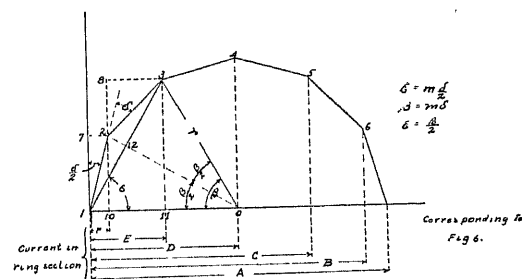


FIG. 7

current distribution in the rings must be related in some manner to a sine law. The exact relations are derived mathematically as follows:

In Fig. 6 the center of the ring section E is β electrical deg. displaced against the point G. It follows that in this case $\beta = 2\delta$. In the same manner the ring point D is displaced by an angle $\beta = 3\delta$, etc. In Fig. 7 the angle β , of Fig. 6 appears as angle 1-0-3, if the ring section E is under consideration; or an angle 1-0-4 if point D is under consideration, etc. From triangle

1-0-3, it follows that the side 1-3 is given by the equation:

$$(1-3) = 2r \sin \frac{\beta}{2} \quad (10)$$

As the ring current in section *E* is a projection of the vector 1-3 on the base line,

$$I_{\beta} = 2r \sin \frac{\beta}{2} \cdot \cos \epsilon \quad (11)$$

But angle ϵ is related to the angle β ,

$$\epsilon = 90 - \frac{\beta}{2} \quad (12)$$

as can be seen from the triangle 1-0-12. Consequently

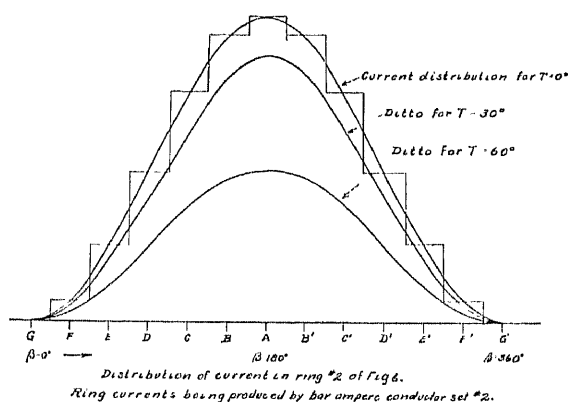


FIG. 8

the cosine of angle ϵ can be expressed as a function of angle β . $\cos \epsilon = \cos \left(90 - \frac{\beta}{2} \right) = \sin \frac{\beta}{2}$ (13)

and this value substituted in equation (11) gives

$$I_{\beta} = 2r \sin^2 \frac{\beta}{2} \quad (14)$$

Making use of the well-known relation

$$2 \sin^2 \frac{\beta}{2} = \left(1 - \cos \frac{\beta}{2} \right) \quad (15)$$

and substituting this into (14), the final equation for the ring current for an arrangement as per Fig. 6 is given,

$$I_{\beta} = r (1 - \cos \beta) = \frac{Z \bar{I}}{\pi} (1 - \cos \beta) \quad (16)$$

This equation gives the ring current in a split ring as function of the angle β (Fig. 6), and which when plotted in coordinate system gives the curve of Fig. 8. Consequently, the loss at any point of the ring is obtained by squaring equation (16) and multiplying it with the coefficient k , which takes care of the resistance of the ring section under consideration, in the manner explained.

The loss at any point of the ring is, therefore,

$$\bar{I}_{\beta}^2 k = r^2 (1 - \cos \beta)^2 k \quad (17)$$

The total ring loss must be the integral of this equation, i. e.,

$$\begin{aligned} \text{loss in one ring per pole pair} &= \int_{\beta=0}^{\beta=360} r^2 k^2 (1 - \cos \beta)^2 d\beta \\ &= k r^2 \left[\int_0^{360} d\beta + \int_0^{360} \cos^2 \beta d\beta - \int_0^{360} 2 \cos \beta d\beta \right] \\ &= k r^2 [2\pi + \pi + 0 - 0] = 3\pi r^2 k \quad (18) \end{aligned}$$

Consequently the loss in one ring per pole pair equals $3r^2 k$, or loss per pole pair and both rings equal

$$6\pi r^2 k \quad (19)$$

Substituting $k = R/2\pi$ from equation (1) and $r = \frac{Z \bar{I}}{\pi}$

from equation (6), we find, losses for both rings per pole

$$\text{pair} = \frac{3 R Z^2 \bar{I}^2}{\pi^2} = \frac{3 R Z^2 \bar{I}^2 \cdot 2}{\pi^2} \quad (20)$$

This equation compared with (8) shows that the ring loss for a current distribution (Fig. 6) is three times as large as the ring loss for a current distribution, (see Figs. 4 & 5).

From the above it follows that the maximum ring current, for a distribution as shown in Figs. 6, 7, and 8, is the sum of all bar currents of one pole; while for the distribution shown in Figs. 3, 4, and 5, the maximum ring current is only the sum of one-half the bar currents of one

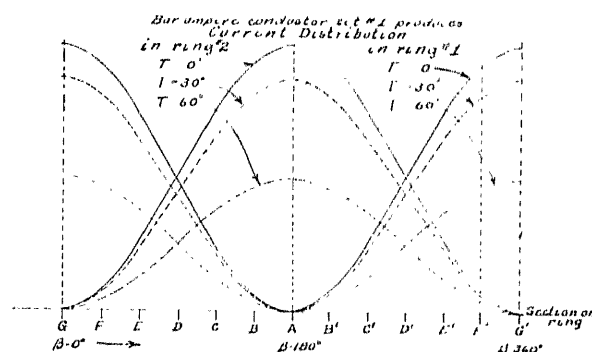


FIG. 9

pole. The losses in one ring must vary from time to time: At one moment the distribution of the ring current in ring No. 2 is that given in Fig. 4, and 90 electrical deg. later the current distribution in the ring No. 2 and bars is as shown in Fig. 5. In order to determine the actual loss in the rings, it is to be remembered that a rotating sine-shaped field can always be considered as being made up of two alternating sine-shaped stationary fields, which are located at right angles to each other and the alternations of which have a 90 deg. time displacement. Consequently, sine-shaped distributed

rotating ampere conductors (bar currents are under discussion) can be considered as being made up of two sets of ampere conductors:

Set No. 1, whose axis is located as per Fig. 4, *i. e.*, the maximum of the ampere conductors coincides with the slot A in the ring.

Set No. 2, whose axis is located as per Fig. 6, *i. e.*, it is 90 electrical deg. displaced from the slot A.

The ampere conductors of each one of these two sets must vary in time according to the sine wave, or cosine law, and the amperes in a given section of a ring must also vary with time in accordance with the sine or cosine law. For instance, for Fig. 4 the ring current distribution in space is given by Fig. 5. For the time $T = 0$, it has been assumed that the current is zero; for the time $T = 90$ deg., the current distribution has reached its maximum; and for the time $T = 30$ and $T = 60$, the distributions lie between the two mentioned extremes.

In a similar manner, current distributions in a split ring vary from time to time. For the time $T = 0$ the distribution is represented by the heavy curve in Fig. 8.

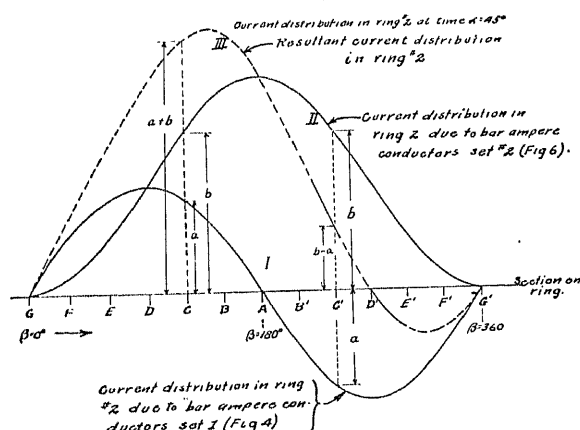


FIG. 10

This figure also shows the distribution for the time $T = 30$ deg. and $T = 60$ deg. For the time $T = 90$ deg., the current distribution is zero and is equivalent to the base-line of Fig. 8 diagram.

In discussing the current distribution in a split ring, reference was made to ring No. 2 in Fig. 6. It remains to be seen if the same current distribution also exists in ring No. 1 of Fig. 6. For reasons of symmetry, the current distributions in rings Nos. 1 and 2 must have the same general shape. However, the curve representing the current distribution in ring No. 1 must be displaced 180 electrical deg. against the curve representing the current distribution in ring No. 2, because it is seen that the current in ring No. 1 is zero at point A and the current in ring No. 2 is a maximum at point A. The distributions of rings Nos. 1 and 2 for a given time instant are given in Fig. 9.

For the unsplit ring, (Figs. 3, 4, and 5,) the current distributions in corresponding sections in rings Nos. 1 and 2 are the same and are not displaced against each other.

In reality the ring distributions, as shown in Figs. 4 and 6, occur simultaneously. Consequently the resultant current distributions in each ring must be the sum of the currents in a given ring section, as found from Figs. 4 and 5, and the current in the same ring section as found from Figs. 6 and 9.

In this manner the distribution of the currents in ring No. 2 is obtained as shown in Fig. 10, where curve I represents the distribution in ring No. 2, due to the ring currents produced by the bar ampere conductor set No. 1, which, in turn, corresponds to the arrangement shown in Fig. 4. The curve II in Fig. 10 represents the current distribution in ring No. 2 due to ring currents produced by the bar ampere conductor set No. 2, which, in turn, corresponds to the arrangement shown in Fig. 6. Curve III, finally, represents the sum of the ordinates of curves I and II and represents for a certain time instant the resultant current distribution in ring No. 2. For a different time instant, the resultant ring distribution has a different shape, as follows:

As the time when ampere conductor set No. 1 is zero, ampere conductor set No. 2 is a maximum. The resultant distribution in ring No. 2 at this moment must be, therefore, as shown in Fig. 8, curve marked $T = 0$. Similarly, for the instant when ampere conductor set No. 1 is a maximum, ampere conductor set No. 2 is zero, the resultant distribution in ring No. 2 is, for this moment, as the curve marked $T = 90$ in Fig. 5. In Fig. 10, a time moment $\alpha = 45$ deg. has been selected, so as to have neither curve I nor II equal to zero. For this time moment, the maximum value of curves I and II happens to be equal to 70.7 per cent of the absolute maximum which they reach for the time $\alpha = 0$, and $\alpha = 90$ deg.

It must be clearly understood that for any other time instant than that illustrated in Fig. 10, the magnitude of the ordinates of curves I and II changes, while the relative shape of curves I and II does not alter. On the other hand, the shape and the magnitude of curve III alters with time. At any instant the resultant current flow in any ring section say, for instance, section C, consists of a current due to the current corresponding to curve I, *i. e.*, equal to a , and a current due to curve II, *i. e.*, equal to b . The total instantaneous current in ring section C is, therefore, $a + b$. The instantaneous loss in the ring section C is proportional to the square of the resultant current and, hence, is proportional to $(a + b)^2$.

If a corresponding ring section C' is selected—which is so located that its distance from the symmetry line A is the same as the distance of the point C from the symmetry line A—the instantaneous current in section C' is $b - a$, and the loss in this section is proportional to $(b - a)^2$. Consequently, it can be said: Loss in section C proportional to $(a + b)^2$

$$= (a^2 + b^2) + 2ab$$

Loss in section C' proportional to $(a - b)^2$
 $= (a^2 + b^2 - 2ab)$.

The combined loss in sections C and C' is the sum of the losses in C and C' and is given by:

$$\text{Loss in section } C \text{ and } C' = 2(a^2 + b^2). \quad (21)$$

This equation demonstrates that the sum of the instantaneous losses in any two symmetrically located ring sections equals the sum of the losses produced independently in each section by the ring currents a and b .

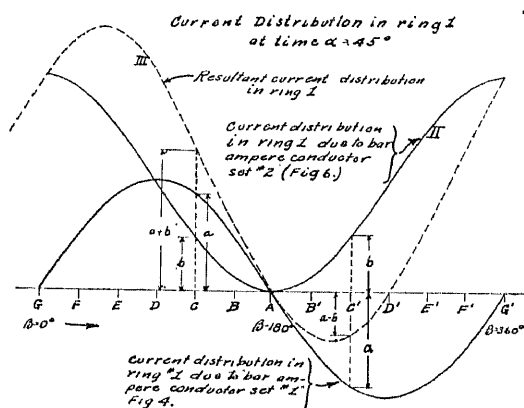


FIG. 11

Consequently, the total losses in ring No. 2, at any moment, is equal to the sum of the instantaneous ring losses due to currents I and II. As the magnitude of the currents represented by curve I, Fig. 10, changes in time according to a sine law, it follows that the losses due to these ring currents change in time as,

$$L_1 = \bar{L}_1 \sin^2 \alpha \quad (22)$$

where \bar{L}_1 is the maximum loss which occurs in the ring, that is, which occurs at the time $\alpha = 90$ deg. Similarly, the currents corresponding to the distribution curve II, Fig. 10, change in time in accordance with the cosine law. The losses due to the currents corresponding to curve II are given,

$$L_2 = \bar{L}_2 \cos^2 \alpha \quad (23)$$

where \bar{L}_2 is the maximum loss which occurs in the ring due to the bar ampere conductor set No. 2. Previously it was shown by equation (20) that a fixed relation exists between \bar{L}_1 and \bar{L}_2 , and that \bar{L}_2 is three times as large as \bar{L}_1 . In other words,

$$\bar{L}_2 = 3\bar{L}_1 \quad (24)$$

The total loss in ring No. 2 at any time α must be the sum of the losses given by equations (22) and (23). Substituting for L_2 the values from equation (24), we obtain,

$$\begin{aligned} L_1 + L_2 &= L_1 \sin^2 \alpha + 3L_1 \cos^2 \alpha \\ &= L_1 (\sin^2 \alpha + \cos^2 \alpha + 2\cos^2 \alpha) \\ &= L = 1 + 2\cos^2 \alpha \end{aligned} \quad (25)$$

The results of equation (25) are graphically represented in Fig. 12. It will be seen that the resultant loss in ring No. 2 fluctuates between the extremes of $3 \times \bar{L}_1$

and \bar{L}_1 . The time intervals between two successive maxima correspond to one-half slip periodicity.

So far the losses were derived for the current distributions existing in ring No. 2. It was shown that the current distribution in ring No. 1 due to bar ampere conductor set No. 2 is the same as in ring No. 2, but is 180 deg. displaced in space against the distribution in ring No. 2, as shown in Fig. 9.

The ring current distribution in rings Nos. 1 and 2, due to the bar ampere conductor set No. 1, are, however, identical in every respect.

Consequently the resultant current distribution in ring No. 1 is as shown in Fig. 11. In Fig. 10 the curve I passes through zero where curve II is a maximum, while in Fig. 11 curves I and II pass through zero at the same point. Selecting again two symmetrically located sections C and C' on the ring No. 1, the instantaneous currents in these ring sections are respectively a and b . The losses in these sections are $(a + b)^2$, and $(a - b)^2$. Consequently, the law that the resultant instantaneous losses are the sum of the instantaneous losses of the ring currents due to bar ampere conductor set No. 1 and the ring currents due to bar ampere conductor set No. 2,—also exists for ring No. 1; and the resultant losses in ring No. 1 must vary in time in accordance with the same law as the resultant losses in ring No. 2. The losses in rings Nos. 1 and 2, therefore, reach a maximum at the same time, and also reach a minimum at the same time. It can be stated that for a given effective bar current the losses in the split rings vary in the relation of 3 to 1 and have maxima at time intervals equal to one-half slip periodicity. In other words, the ring losses fluctuate in time with double-slip frequency.

Equation (25) gives the mathematical expression for the variation of the losses as function of time α . This

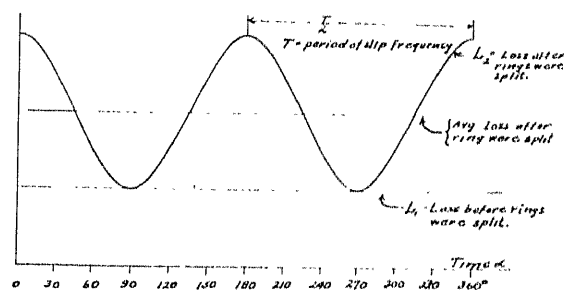


FIG. 12

equation contains the factor $\cos^2 \alpha$. It is a well-known fact that the average ordinates of a $\cos^2 \alpha$ curve are one-half of the maximum ordinates. Consequently the average loss in the rings is given by the equation,

$$(L_1 + L_2)_{avg.} = 2\bar{L}_1 \quad (26)$$

This equation shows the important fact that the average ring loss in a squirrel-cage with split rings is

two times as large as the losses in an unsplit ring, as long as the effective currents in the bars are kept constant.

As these laws are derived for the losses occurring with a given effective current in the bars, it is evident that the same laws also apply to the resistance which the split rings of the squirrel-cage offer. It is, therefore, correct to say *the ring resistance of a squirrel-cage with split rings varies in the ratio of 3 to 1 with a frequency of*

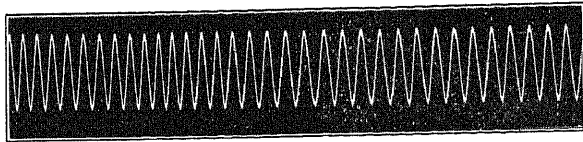


FIG. 13

two times slip frequency. The average ring resistance is equal to two times the resistance of an unsplit ring.

Consequently with *absolutely constant rotor speed*, the effective value of the bar currents fluctuates with double-slip frequency, which in turn means that the rotor torque fluctuates with double-slip frequency. Such a condition exists when the inertia of the rotor and the driven machinery is very large and tends to keep the rotor speed constant in spite of the fluctuating torque which acts on the rotor.

On the other hand, when the rotor and the driven machine have infinitely small inertia and the mechanical load torque is held constant, the slip of the machine must vary periodically and the rotor bar currents remain constant in order to produce constant torque.

In the latter case, an oscillogram of the primary line current must show a constant magnitude of alternating current. In the former case, where the inertia is infinitely large, the oscillogram of the line current must

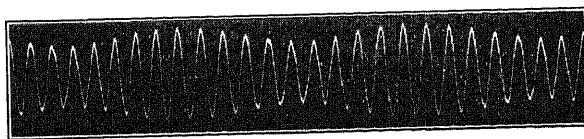


FIG. 14

show a variation of the a-c. value and the magnitude of this alternating current fluctuates periodically in time.

In practise the conditions lie between the two extremes just discussed, that is, the speed and the current changes. As a rule these changes will not be found very objectionable.

The higher the average slip, the faster are the torque impulses, and the greater is the tendency for the machine to run at constant speed.

An oscillogram of the full load line current taken on a 7½-hp., four-pole, 60-cycle, 2-phase, 220-volt, squirrel-cage motor with split rings is shown in Fig. 14. The fluctuations in the magnitude of the line current is

clearly shown in this oscillogram. Fig. 13 shows the line current on the same machine, but provided with a squirrel-cage without split rings. No fluctuations whatsoever are noticeable in this case in the magnitude of the line current.

At the same time that the oscillogram of Fig. 14 was taken, the slip on the motor was also observed and found to be 4.4 per cent. It was measured by the stroboscopic method, and the white cross on the pulley used clearly showed a periodic swing, indicating that the speed of the motor fluctuated. The relations on the motor under test were such that the inertia was not sufficiently great to damp out completely the speed fluctuations. The oscillogram shows that the time

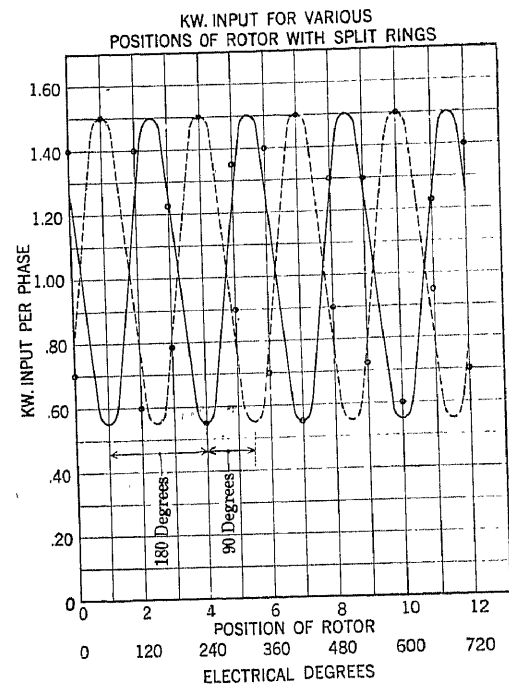


FIG. 15—7½ HP.—4 POLE—220 VOLT—60 ~2 ϕ
1725 REV. PER MIN.

between two current maxima, A and C, equals approximately 11 times the time between two adjacent 60-cycle current maxima, A and B. Consequently, the periodicity of the "breathing" of the line current is $1/11 = 9.1$ per cent or $9.1/4.4 = 2.06$ times the measured slip frequency. The theoretical value of this ratio according to the above theory is 2. The agreement between test and theory is satisfactory.

Fig. 15 gives the kw. input to phases No. 1 and 2 when the rotor is locked and the rings are split. The results are plotted as function of rotor position. This plot shows that the kw. input of a given phase depends on the position of the rotor, and the maxima are displaced one-pole pitch or 180 electrical deg. This is in full agreement with the theory. The plot also shows that the maxima of phase No. 1 is displaced 90 electrical deg. against the adjacent maxima of phase No. 2. This also is in full agreement with the above theory, which

shows that the minimum, or maximum, resistance of the squirrel-cage corresponds to two a-c. fields 90 electrical deg. displaced against each other.

From the maximum readings from phase No. 1, (corresponding to position 1-4-7), and the minimum reading of phase No. 2 (corresponding to the same rotor position), it is calculated that the equivalent rotor resistance expressed in primary turns is 1.62 for phase No. 1 and 0.565 for phase No. 2. Consequently, the ratio of resistance variation is $1.62/0.565 = 2.82$. The theory showed that the rotor resistance, when only the rings are considered, must vary in the ratio of 1 to 3; but if the bars also are considered, the resistance naturally must vary in a ratio less than 1 to 3. The theory, therefore, agrees with the results found by test.

Fig. 15 further shows that the sum of the input to phase No. 1 and to phase No. 2 is practically constant or, in other words, the total average torque on the rotor is practically independent of the rotor position. For rotor position 1.6, 3.15, 4.7, 6.3, etc., the input to phase No. 1 is equal to that of phase No. 2. For one of these positions, a locked test was taken and the results are plotted in the form of a circle diagram (Fig. 16). The diameter of the circle of this diagram corresponds to 38 kv-a.

A similar test was made on the motor using rings which were not split, and the results are shown in the circle diagram of Fig. 17. The circle in this diagram has a diameter of 48.3 kv-a. Splitting the rings reduced the diameter of the circle from 38 to 48.3, or

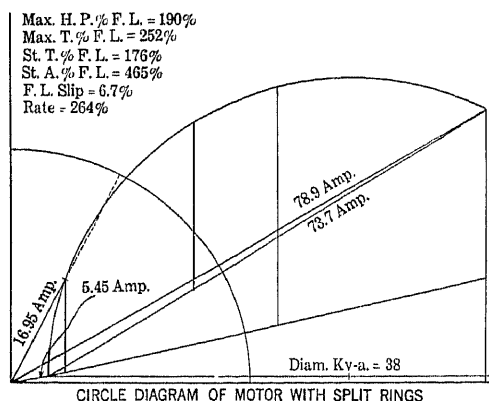


FIG. 16—7½ HP.—4 POLE—220 VOLT—60 ~2 Φ
1725 REV. PER. MIN.

to a value of 79 per cent of the original value before the rings were split. This is equivalent to stating the leakage of the motor with split rings is $1/1.27 = 0.79$ times that of the same motor before the rings were split. Similar tests made on a number of other machines of different ratings and speeds also have shown an increase in leakage. It is, therefore, justifiable to say the splitting of the rings not only increases the average ohmic resistance of the rings in the ratio of 1 to 2, but also increases the leakage of the machine. Conse-

quently, the actual gain in starting torque due to splitting the rings must be less than the increase in average rotor resistance. In the machine whose test data are recorded in this paper, the increase in leakage counteracted completely the increase in rotor resistance, and the net result was that the rotor with split rings had a starting torque corresponding to 10.68 kw., while the same motor with rings which were not split had a starting torque corresponding to 11.4 kw. Splitting the rings in this particular case increased the leakage so much as to more than counteract the increased rotor

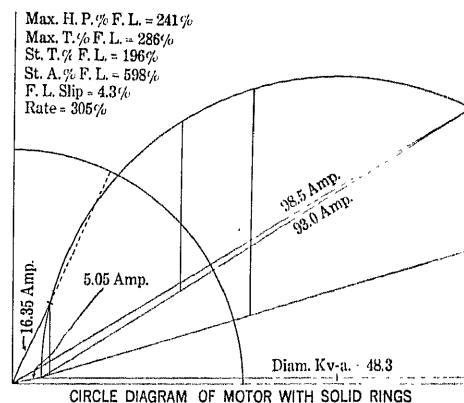


FIG. 17—7½ HP.—4 POLE—220 VOLT—60 ~2 Φ
1725 REV. PER. MIN.

resistance. The starting torque of the motor provided with split rings was less than that of the motor with rings which were not split.

The only beneficial effect obtained by splitting the rings in this case was a better torque per ampere. Before the rings were split, the torque per ampere was $11.4/9.85 = 1.16$; and after the rings were split, the torque per ampere was $10.68/7.89 = 1.35$. It is self-evident that the increase in leakage and rotor resistance must be followed by a decrease in maximum hp. output. For the tested machine, the circle diagrams show that the split rings decreased the maximum hp. to 78 per cent of the value which existed before the rings were cut. This figure, derived from the diagram, checked very closely with an actual brake test taken on the machine.

Discussion

D. D. Clarke: I was very much interested in Mr. Weichsel's paper, because of the rather novel presentation of what, in the field, we think of as a repair trick to make a motor start a given load. I felt, in reading the paper, that Mr. Weichsel did not intend this as a normal production motor. The operating company has a contact with this motor that the manufacturer might not think important, and that is the varying current or breathing effect, as Mr. Weichsel puts it.

This breathing occurs three to five times per second and incandescent lamps are particularly sensitive to such breathing of the voltage. Even though it may vary only a half or one per cent, this, in a critical location, could make a very unsatisfactory condition on a public utility's lines. The difficult thing would be that replacement would be required to correct it. In a way, it is

parallel to a trouble job on a wound-rotor motor where the secondary winding is open. This same sort of breathing action takes place because of the variation in the losses in the secondary of the induction motor.

Tampering by a repair man with the design features of a motor, does not improve conditions. In this case, the horsepower rating of the motor was reduced and the actual starting power was reduced.

K. L. Hansen: It has been clearly brought out in the paper that the splitting of the end rings in the manner suggested has certain detrimental effects on the operation of the motor when running at its normal load and speed. For that reason it has apparently been very little used. Nevertheless it may at times be the means of overcoming some specific difficulty, and it therefore becomes very desirable for a designing engineer to know just what can be expected in the way of remedying the trouble, as well as the detrimental effects that are likely to result from the application of this method. I feel, therefore, that the author deserves credit for analyzing this problem.

With regard to the method used in the paper of arriving at the resistance of the end rings, perhaps, some might prefer to use shorter and more direct methods. For example, it can be seen at once from Fig. 4 in the paper that the maximum current in the ring at Section D is the sum of the average current in the rotor bars over one-half the pole pitch. Using Mr. Weichsel's notation of \bar{I} to denote the maximum current in the rotor bars, the

average current then is $\frac{2\bar{I}}{\pi}$. If Z be the number of bars over

one pole pitch, the maximum current in the end ring will then be

$\frac{Z\bar{I}}{\pi}$. From this it follows that the effective current in the end

ring is $\frac{Z\bar{I}}{\sqrt{2}\pi}$. Squaring this and multiplying by $\frac{R}{2}$, this be-

ing the resistance spanning one pole pitch, we have $\frac{R Z^2 \bar{I}^2}{4 \pi^2}$

as the losses per pole in one ring, which is identical with the result arrived at in the paper.

In the same way inspection of Fig. 6 of the paper will show that the maximum current in the ring in this case is equal to the sum of the average current in the rotor bars taken over one whole pole pitch, or twice as high as with the distribution shown in Fig. 4. It will also be seen that at any given instant the current in the end ring is always in the same direction. The current distribution in the end ring in this case varies sinusoidally from zero to a maximum value equal to twice that of the previous case, and hence can be expressed by

$$\frac{Z\bar{I}}{\pi} - \frac{Z\bar{I}}{\pi} \cos \beta$$

where β is the angle in electrical degrees measured along the end ring with the section G taken as reference. This current is seen to consist of two components, the first one being constant and

having an effective value, $\frac{Z\bar{I}}{\pi}$, the second one varying sinu-

soidally and having an effective value, $\frac{Z\bar{I}}{\sqrt{2}\pi}$. The loss due to

this current distribution is the sum of the losses of these two components and the loss per pole in one ring is, therefore,

$$\left(\frac{Z^2 \bar{I}^2}{\pi^2} + \frac{Z^2 \bar{I}^2}{2 \pi^2} \right) \frac{R}{2} = \frac{3 R Z^2 \bar{I}^2}{4 \pi^2}$$

which is seen to be three times as high as the losses corresponding to the current distribution shown in Fig. 4.

That the losses in the end ring due to "ampere-conductor set No. 1" and those due to "ampere-conductor set No. 2" can be considered separately may also be briefly shown by a similar line of reasoning. However, to some these shorter methods may not seem sufficiently conclusive, in which case they have recourse to the more detailed methods used by Mr. Weichsel in his paper.

It has then been shown that with the end rings split as suggested the rotor may be considered as being made up of two distinct circuits displaced 90 electrical deg. from one another and one circuit having an end-ring resistance three times as high as the other. In other words, the case is exactly equivalent to a slipping motor with two-phase rotor and unequal resistances in the two phases. If I_1 be the current flowing in the circuit of low resistance and I_2 the current flowing in the high-resistance circuit, the magnetizing force of the combined rotor currents can be shown to consist of two components, a forwardly rotating com-

ponent equal to $\frac{\bar{I}_1 + \bar{I}_2}{2}$ and a backwardly rotating component

equal to $\frac{\bar{I}_1 - \bar{I}_2}{2}$.

This backwardly rotating component of rotor m. m. f. rotates on the rotor at a speed corresponding to slip frequency, but as the rotor is slipping behind the main rotating field at the same rate, it follows that the relative motion between the main field and the backwardly rotating magnetizing force must be equal to twice the slip. As the poles of this magnetizing force pass the poles of the main rotating field of the same and alternate polarities, a pulsating torque is developed, the rate of pulsations being equal to twice the slip frequency. The amplitude of this torque pulsation is proportional to the product of the main field and the backwardly rotating component of the rotor m. m. f. It is responsible for the pulsations in the speed and line current discussed by Mr. Weichsel.

Besides being responsible for the speed and torque pulsations, this backwardly rotating component of the secondary magnetic field, causes some other interesting phenomena that have not been brought out in the paper. The average value of the torque pulsations is zero and the speed-torque curve is not affected by them. This curve may, nevertheless, be greatly modified by the backwardly rotating component of the secondary field. This can, perhaps, be best observed by taking an extreme case of unbalancing of the rotor circuits, that is by opening one of these circuits entirely and running the machine with single-phase rotor. In that case the backwardly rotating component of secondary m. m. f. is equal to the forwardly rotating component.

The backwardly rotating component of rotor m. m. f. produces a magnetic field of greater or less intensity, which generates a current in the primary of frequency $(2s - 1)$ times the line frequency, where s is the slip. The voltage generated in the primary winding being proportional to the frequency, becomes equal to zero at half speed.

The intensity of the backwardly rotating field depends on the strength of the m. m. f. producing it and on the reaction of the current produced by it in the primary circuits. As there is no current generated in the primary by this field at half speed, it reaches its maximum intensity at this point and would reach very high values if it were not limited by saturation. The fact that saturation enters in and greatly modifies the mutual inductance between primary and secondary windings near the half-speed point makes the torque developed by the backwardly rotating field somewhat difficult to calculate in this region.

However, as soon as the speed departs, even slightly, from the half-speed point, currents will flow in the primary which by their damping action reduce the field strength below the saturation point. Under these conditions it can readily be seen that if I_1 be the secondary current in terms of the primary, the current generated by the backwardly rotating field is

$$I_o^1 = I_1 \left[\frac{(2s-1) X_m}{r_o + j(2s-1)(X_m + x_o)} \right]$$

where X_m is the mutual reactance at full frequency, r_o the primary resistance, and x_o the primary reactance. The primary resistance loss resulting from this current divided by $(2s-1)$ gives the torque (synchronous watts) developed by the backwardly rotating field at any speed. Below half speed this torque component is in the same direction as the motor torque, at half speed it becomes zero, and above half speed there is a generator action and it is in opposition to the main motor torque. For example, in Fig. 1 herewith is shown the speed-torque curve of a

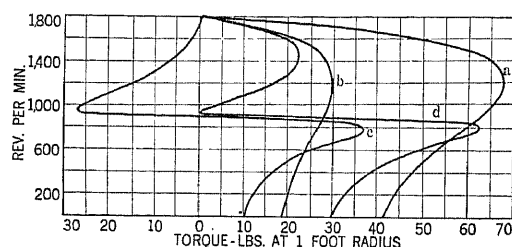


FIG. 1

motor operating on single-phase secondary and having approximately the same constants as the motor used for illustration in Mr. Weichsel's paper. Curve *a* is the torque curve with balanced polyphase secondary. Curve *b* is the torque developed by the forwardly rotating field when operating with single-phase secondary, and curve *c* is the torque developed by the backwardly rotating component. The resultant of the last two, curve *d*, is the actual speed-torque under this condition.

It will be noticed that the resultant torque is zero at half speed, and if started from standstill the motor will not accelerate past this point unless external means are employed. Whether or not a motor will in general stick at half speed when operating on single-phase secondary depends on the secondary resistance. Is this is relatively high the motor may come up to full speed.

It should also be observed that the torque pulsations are most prevalent when the damping effects of the currents induced in the primary reduce the intensity of the backwardly rotating field to a low value, as for example near synchronism. When this damping effect is small, so that the backwardly rotating field approaches the forwardly rotating field in intensity, as for example near the half-speed point, the torque pulsations disappear.

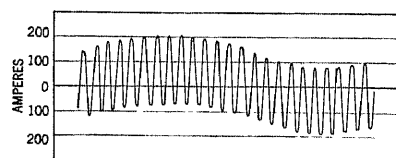


FIG. 2

A number of interesting points about a motor operating under this condition have been brought out by Gazda in a paper *Performance of Polyphase Induction Motors under Unbalanced Secondary Conditions*, (A. I. E. E. TRANS., Vol. XXXVI, 1917, p. 339). An oscillogram in that paper of the primary current taken with a rotor running at half speed plainly shows the low-frequency component generated by the backwardly rotating field of the rotor. It does not show any evidence of torque pulsations causing variations in the amplitude of the primary current similar to those indicated in the oscillogram shown by Mr. Weichsel which was taken with the motor running near

synchronism. Fig. 2 herewith shows part of the oscillogram reproduced from Mr. Gazda's paper.

Fig. 3 herewith shows three speed-torque curves, also reproduced from the same paper, taken on a 50-hp., 60-cycle, six-pole motor. Curve No. 1 was taken with all three phases of the rotor short-circuited, curve No. 2 with balanced resistances in the three rotor circuits, and curve No. 3 was taken with single-phase secondary. It is interesting to note that the falling off of speed with increasing load is smaller when the machine is operating at half speed on single-phase secondary than when operating near synchronism with all the rotor phases short-circuited.

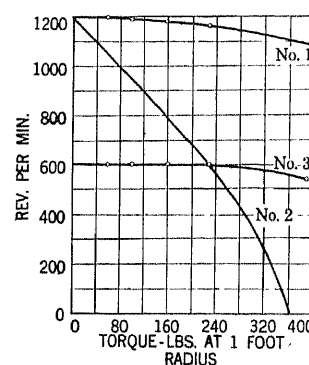


FIG. 3

Returning now to the case of a rotor with split end rings, or unbalanced rotor resistances, it is evident that the phenomena of single-phase rotor operation enter in, only, of course, to a much less marked degree. The current generated in the primary can in that case be approximately expressed by the following formula

$$I_o^1 = \frac{I_1 - I_2}{2} \left[\frac{(2s-1) X_m}{r_o + j(2s-1)(X_m + x_o)} \right]$$

Fig. 4 herewith shows how the speed-torque curve would be modified on a motor similar to that discussed by Mr. Weichsel. Below half speed the torque will in general be increased so that the accelerating torque in that range is greater. At half speed there is a dent in the speed-torque curve and above half speed the torque will be considerably less than with normal operation. The detrimental effects are, therefore, as pointed out in the paper, reduced speed at full load, reduction in maximum power output, and reduced maximum torque in the upper stable range of the speed-torque curve.

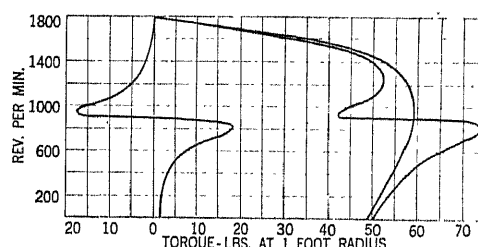


FIG. 4

The starting torque, it appears, may be increased or slightly reduced. Even when the starting torque is reduced, which would seem to be rather the exceptional case, the accelerating torque in the range from standstill to half speed is in general increased. This may in some instances be helpful in overcoming trouble due to sub-synchronous speeds, and the scheme has occasionally been used for this purpose.

The following figures given me by Mr. Oesterlein will show the locked readings on a motor on which the end rings had been split to overcome trouble due to sub-synchronous speed.

Before splitting the end rings—438 volts, 5.4 amp., 3.32 kw., 81 per cent power factor, 10.7 ft.-lb. torque.

After splitting the end rings—440 volts, 4.25 amp., 2.53 kw., 77.5 per cent power factor, 12.25 ft.-lb. torque.

In addition to showing a higher starting torque after splitting the end rings, the motor accelerated its load much more rapidly than when solid end rings were used.

Mr. Weichsel mentions only one beneficial effect from splitting the end rings, namely that of better starting torque per ampere. I believe we would be justified in adding one more, that of better accelerating torque.

J. L. Hamilton: As Mr. Weichsel has pointed out, the results of tests and analysis on squirrel-cage motors with split-end-ring rotors give, as one would expect, the effect of a high-resistance rotor.

His curves and data show lower maximum torque, lower maximum horsepower, and higher static torque per ampere for the rotor with split end rings.

The data show the magnetizing current with split end rings as being about 8 per cent higher than for solid end rings. One would expect the magnetizing current to be substantially the same.

Mr. Hansen in his discussion of this paper has very well pointed out the tendency for sub-synchronous load torque points when rotors with split end rings are used.

On account of the heavy static and pull-in torque requirements for induction motors, along with a minimum of starting current, it is necessary for the designer to avoid low-torque points very carefully. A designer, therefore, would be very careful in employing split-end-ring rotors in general-purpose motors. Central-station engineers are very desirous of keeping static and starting currents of motors to a minimum and would not look with favor, of course, on a motor with low-torque points, since this would mean large starting current per unit of starting torque.

P. L. Alger: (by letter) I think the general conclusions we may draw from this paper are, first, that any dissymmetry of the rotor design introduces so much extra reactance as to be distinctly harmful, and, second, that any dissymmetry in the rotor causes double-slip-frequency pulsations of torque and of line current. Practically all single-phase motors have a distinct double slip frequency "beat" in the noise they produce. It is probable that this beating is due to rotor dissymmetries.

It has often occurred to me that any dissymmetries in the rotor, or the use of high-impedance end rings, may cause cross currents to flow between squirrel-cage bars through the rotor punchings, and that these currents may account for various secondary phenomena, such as extra losses. Early induction motors were nearly all provided with insulated squirrel-cage bars, and this practice is still followed by many European manufacturers, the idea being presumably to avoid the possible detrimental effects of such cross currents between bars.

I should like to inquire whether Mr. Weichsel has had any experience indicating that these currents are of appreciable magnitude. I should think that they would be sufficiently large with a split-end-ring construction to affect materially the motor performance.

W. L. Upson: I think that we might find, one of these days, when we go over this paper from another point of view, that we might want to extend the investigation and exaggerate the very defects that are outlined here. For example, some use might come of exaggerating the pulsations in connection with induction generators, or perhaps if we made some other splits in the rings, differing from the 90-deg. splits that the author has mentioned. I therefore want to put in this thought, that we have here an extension of our knowledge that later on may be of direct value to us.

B. T. McCormick: Mr. Hansen has suggested a "short-cut" method of obtaining the effective resistance of a squirrel-cage rotor, which is similar to the method which I have always used.

However, I have never had occasion to determine the resistance of a split-ring squirrel-cage rotor, either by the method suggested by Mr. Hansen or by any other method.

Mr. Hansen calls attention to the tendency of this motor to partake in some degree of the peculiarities of a motor with a single-phase rotor, and its probable tendency to hang at half speed. Mr. Weichsel did not make any experiments on this motor to determine its torque at intermediate speeds, and I am inclined to agree with Mr. Hansen that this motor might have some tendency to hang at half speed, but whether slight or decidedly marked, I cannot say.

Mr. Hansen also remarked that the leakage reactance of this motor is the same as that of a normal motor and that the greater leakage reactance mentioned in Mr. Weichsel's paper is really not such, but merely an effect due to the presence of a backward rotating component. This is merely another way of describing the same action. It is usually easier to combine all the various actions and express their effect as one net result, and the best method of stating the present action is to say that the machine, when tested, gives a circle of smaller diameter than the standard motor, which means that in effect it has a greater leakage reactance.

Mr. Alger asked regarding the effect due to stray currents brought about by not having insulated rotor bars. No investigation along this line has been conducted. I can easily imagine that there would be a tendency for the currents to stray from their proper paths in the squirrel-cage winding in an endeavor to find short cuts through the iron, to follow as closely as possible the natural symmetrical current distribution of the standard squirrel-cage construction. Some effect of this kind probably takes place, and if one were to build two split-ring squirrel-cage rotors, one with uninsulated bars and another with insulated bars, it would not be surprising to find that these rotors when tested show somewhat different performances.

There is one other point that I am rather surprised has not been mentioned by someone, and that is the difficult problem of bracing the split rings to withstand the action of centrifugal force, especially at high speeds. This, I think, is one of the most important criticisms against this type of rotor.

R. E. Hellmund: (communicated after adjournment) In the beginning of the paper by Mr. Weichsel, the assumption is made that the currents in the squirrel-cage bars are distributed according to a sine curve (see Figs. 2, 4, and 6). This assumption is not quite correct, as is shown in the accompanying Figs. 5 and 6.

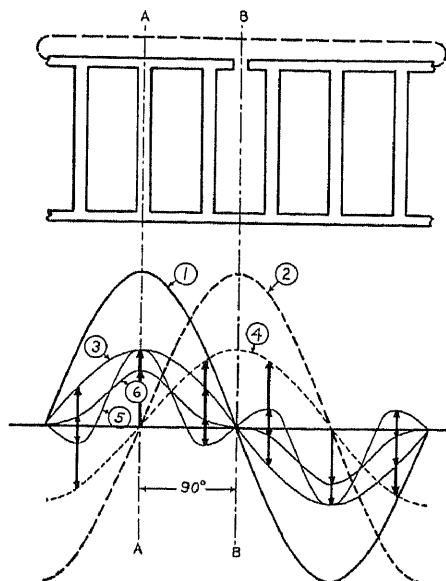
In order to simplify the matter as much as possible, a two-pole rotor with three squirrel-cage bars per pole has been assumed. Under the assumption of a sinusoidal primary field, the voltages in the squirrel-cage bars can be assumed to follow a sinusoidal curve. The currents flowing in the bars have then been calculated by a simple application of Kirchhoff's laws, first assuming that all the resistance is in the bars; secondly, that all the resistance is in the rings; and thirdly, that the resistance is equally distributed between the bars and the rings. The results of this calculation are shown in Fig. 6. It will be seen that while the currents correspond to a sine curve in the axis (*BB*), such is not the case in the axis (*AA*) except in the case where all the resistance is in the bars.

These data are not given primarily to indicate that the results derived in the paper depart materially from actual facts. This I have not checked in detail, and I believe that unless the resistance of the end rings is a very material part of the total, most of the conclusions given in the paper are essentially in line with facts. The principal reason for showing the attached Fig. 6 is that it permits the bringing out of a number of points not touched upon in the paper.

The figure shows that with currents as actually flowing under different conditions, the rotor m. m. f. is different in the two axes at right angles to each other and that such difference is influenced

by the percentage of the total resistance put into the end rings. This feature of the secondary m. m. f. is the same condition as would be obtained, for instance, in a two-phase wound secondary having different resistances in the two phases. In other words, the splitting of the end rings brings about conditions which are equivalent to an unbalanced wound secondary. This being the case, a number of facts can be derived which have been fully appreciated for some time in connection with unbalanced wound secondaries.

An extreme example of unbalanced wound secondary is a single-phase secondary. This case has been described in a very



FIGS. 5 AND 6

1. Bar voltages at one instant of time
2. Bar voltages 90 deg. later
- 3 and 4. Bar currents, all resistance in bars
- 5 and 6. Bar currents, all resistance in end-rings
- 6 and 4. Bar currents, resistance equally divided between bars and end-rings

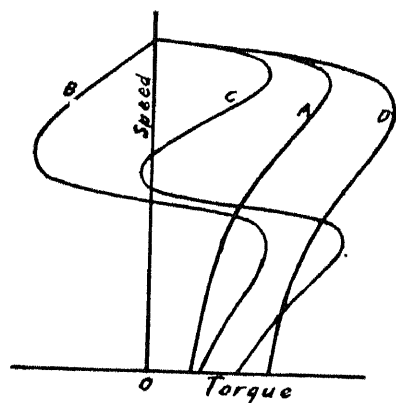


FIG. 7

simple manner by B. G. Lamme in an article in the *Electric Journal* of September, 1915. Fig. 7 given here is reproduced from this article.

It will be recalled that the resultant speed-torque curve *C* of the motor with single-phase secondary is the sum of two component curves *A* and *B*; curve *D* represents the same motor with polyphase secondary. If the secondary is not single-phase but merely unbalanced polyphase, the same conditions apply qualitatively, but to a lesser degree quantitatively. In other words, the curve *C* will not actually indicate negative values above one-half synchronous speed, but there will merely be low

torque points, or what are commonly called "cusps," in the speed-torque curve.

It follows from the above that the same conditions may be expected with the slotted-end-ring squirrel-cage construction. It also seems that the increased apparent leakage mentioned in the paper, resulting in starting torque smaller than expected, may be explained partly by the character of the speed-torque curve with unbalanced secondary (see Fig. 7). Furthermore, since the field form of the rotor in axis *A-A* is materially different from that of the stator, appreciable differential or belt leakage has to be expected. Finally, there is some increased leakage around the end rings.

Fluctuations in primary current of twice slip frequency, as found by Mr. Weichsel, are also obtained in motors having unbalanced secondary phases. This effect, which again can best be demonstrated by reference to the extreme case, namely, a single-phase rotor, may be explained as follows: Consider the rotor running with a low slip. The single-phase currents in the rotor set up a pulsating field, which may be resolved into two fields rotating in opposite directions at a speed, relative to the rotor, corresponding to slip frequency. These two fields induce voltages in the primary of two different frequencies. One field rotates in the same direction as the rotor, adding the slip-frequency speed to the mechanical speed to induce a voltage of line frequency in the stator. The other field, rotating against the rotor, subtracts the slip-frequency speed from the mechanical speed ($1 - S$), inducing in the stator a voltage of a frequency equal to the line frequency minus twice slip frequency. Thus, two voltages, differing from each other by twice slip frequency, are induced in the primary. In general, two voltages of nearly the same frequency acting on the same circuit produce variations, or "beats," in the current of a frequency equal to the difference in the two frequencies. In our case of a polyphase induction motor with single-phase or unbalanced secondaries, this "beat" frequency is twice the slip frequency, as explained above. These beats may or may not have a disturbing influence of practical importance on the line voltage. It is to be expected that in the majority of cases the influence is not of practical importance because wound-secondary motors are frequently operated with unbalanced secondaries without causing much disturbance.

Finally, attention may be called to the fact that the circle diagram does not give entirely correct results with unbalanced secondary, and therefore not with the cut end-ring construction either. The greater the unbalance of the secondary, the greater the discrepancy will be, and in the case under consideration it would appear that the greater the proportion of resistance in the end rings to the total rotor resistance, the greater the discrepancy should be. Referring once more to Fig. 6, it will be seen that the extreme case having all resistance in the end rings has very marked higher harmonics (see curve 5, for instance). It is not unlikely that such a condition may also bring about low-torque points, or cusps, at points other than the one above one-half synchronous speed.

G. L. Hoard: (by letter) This paper will not receive the attention which its excellence merits because the results of the investigation described are negative, that is, negative in the sense that the possibilities of the motor investigated are not very promising. This does not lessen the value of the paper, however. It is quite as important to know the limitations of a particular apparatus as to know its possibilities. The author is to be congratulated on the clear, concise manner in which the subject is presented.

As for the motor itself, it seems to give little promise in the way of improvement in induction-motor characteristics. Its only advantage apparently is an increased torque per ampere, but this advantage is much more than offset by the disadvantages of lower starting torque, lower breakdown torque, and lower maximum output. There is also one other possible disadvantage which is not mentioned in the paper. The heating in the rings

is not uniform. The loss at section A of ring 2 in Fig. 6 will be considerably larger than at points near the cut in the ring. This is not likely to be a serious objection in a rotor structure, having the high thermal conductivity and good ventilation characteristics possessed by the squirrel cage. It would be objectionable, however, in any form of wound rotor. I should like to ask if there was any evidence of local heating in any of the tests run on the experimental motors?

II. Weichsel: Mr. Hoard pointed out that the heating in different sections of the rings must be different. This statement is correct. The current distribution in the different sections of the ring, determined by the method outlined in my paper, when plotted against time, is given in Fig. 8. It will be seen from the

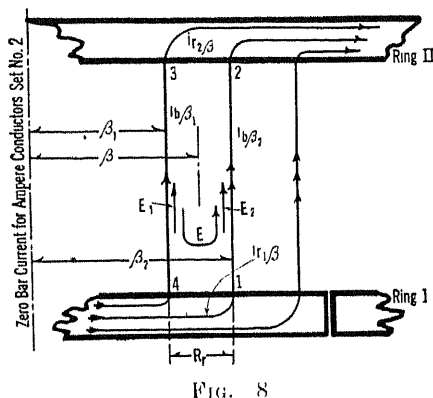


FIG. 8

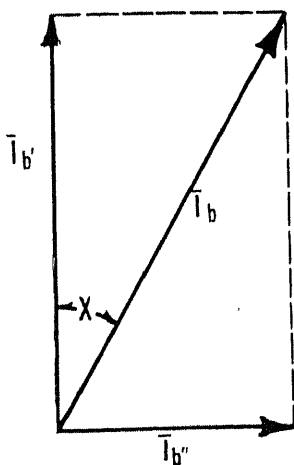


FIG. 9

figure that the maximum heating occurs in the section A of Fig. 6 of my paper. Unfortunately, during the tests, no attention was paid to this phenomenon, which no doubt must exist.

In the discussion, references were made to the effect of non-insulated rotor bars. My experience has shown that in larger machines, even when a standard squirrel cage is used, quite appreciable currents flow during the starting period from the rotor bars into the laminations when the bars are not insulated. I know of instances where during the starting period very noticeable sparks occurred between the bars and the laminations. The heavy starting currents set the bars into vibration and, therefore, the contact between laminations and bar varied rapidly, and this resulted in quite visible sparks. If this condition exists in a standard squirrel cage, there is no doubt that the same condition exists in a much more pronounced manner in a squirrel cage with split rings.

Different discussors also have pointed out the similarity between a squirrel-cage rotor with split rings and a wire-wound

armature with unbalanced resistance in the rotor. This similarity is correct. The tendency to a saddle formation in the speed-torque curve as pointed out by subsequent discussors doubtless exists in the machine with split rings in the same manner as in a machine with wire-wound armatures and unbalanced rotor resistances.

Mr. Hellmund referred to a point which is theoretically of greatest importance. He pointed out that the solution offered in my paper is based on the assumption that the current distribution in the bars follows a sine wave and that there is a possibility that this is not the distribution which actually exists in the bars.

In order to obtain an inside view of the actual distribution of currents in the bars, he applied the Kirchhoff laws to a squirrel cage having only three bars per pole and determined for this structure the current distribution in the rings and the bars under

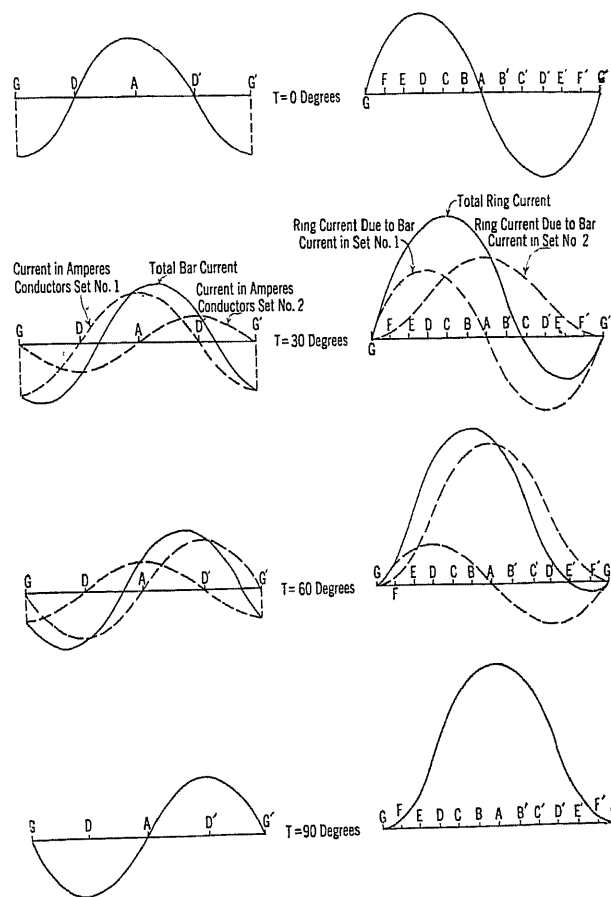


FIG. 10—BAR CURRENTS AND RING 2 CURRENTS

the assumption that the e. m. fs. generated in the bars are of sine-shape distribution. This method of attack is perfectly correct, but I believe that the results obtained in this manner should not be generalized and applied to that problem of my paper, which deals with the current distribution in the squirrel-cage rotor having an infinite number of bars and split resistance rings.

There is no doubt that the voltage generated in the bars due to the relative movement of the bars against a sine-shape rotating field must have a sine-shape distribution in space.

In my paper the first Kirchhoff law, that the sum of all currents must be zero, has been fulfilled, as the whole problem was attacked by determining the ring currents by adding all the bar currents which flow into the ring.

Therefore, if it should be possible to prove that with the current distribution obtained in this manner, the voltage distribution along the bars and rings is such as to satisfy the second Kirchhoff

law, that is, "the sum of all voltages must be zero," it is evident that the assumed current distribution in the bars and the distribution in the rings as set forth in the paper is the actual distribution.

Let us consider a section of the squirrel cage as shown in Fig. 8 herewith. The distribution of the resultant current in the rings and bars is shown by arrows in agreement with the distribution found in my paper. For the local circuits, 1-2-3-4, we can write the second Kirchhoff law in the following form:

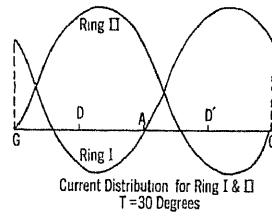


FIG. 11

$$E_2 - E_1 = E = i_{b\beta_2} \cdot r_b - i_{b\beta_1} \cdot r_b - i_{r\beta_2} \cdot R_r + i_{r\beta_1} \cdot R_r \quad (1)$$

which can be rewritten in the form:

$$(E_2 - E_1) - r_b (i_{b\beta_2} - i_{b\beta_1}) = R_r \{ i_{r\beta_2} - i_{r\beta_1} \} \quad (2)$$

where E_1 and E_2 are the voltages generated in bar 3-4, respectively bar 1-2. As the rotating field has a sine-shape space distribution, the voltages E_2 and E_1 must also have a sine-shaped space distribution. According to the assumption made in my paper, the bar currents, i_b , have a sine-shape space distribution. It is evident that under these conditions the difference of the e. m. f. which is left when subtracting the ohmic drop in the bars from the voltage generated in the bars must also follow a sine law—in other words, the left-hand side of Equation (2), must be a sine function. Consequently in order to satisfy the second Kirchhoff law, the right-hand side of the equation must be of the same character as the left-hand side. If it should be possible to prove that the ohmic drop in the ring section 2-3 and 1-4 is equal to the voltage difference between the bars 1-2 and 3-4 when considering only the volts generated and the ohmic drop in these bars, then it is proved that the assumed sine-shape distribution in the bars actually requires potentials along the whole squirrel cage which satisfy the second Kirchhoff laws.

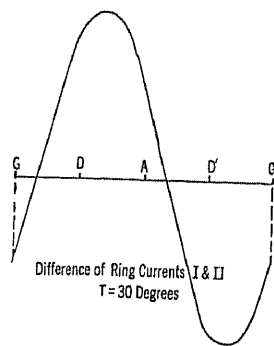


FIG. 12

If the bar current distribution in ampere conductor set No. 1 of the original paper follows a sine law as per:

$$i_{b\beta'} = I_b' \cdot \cos \beta \quad (3)$$

where angle β is measured from the point G in Fig. 4 in the paper, then the ampere distribution in the ampere conductor set No. 2 follows the equation:

$$i_{b\beta''} = I_b'' \cdot \sin \beta \quad (4)$$

The resultant ampere distribution in the bars is given by equation:

$$i_b = I_b' \cos \beta + I_b'' \sin \beta \quad (5)$$

But the maximum bar currents I_b' & I_b'' for set No. 1, set No. 2, respectively are related to the maximum resultant bar current I_b by equations:

$$I_b' = I_b \cos x \quad (6)$$

$$I_b'' = I_b \sin x \quad (7)$$

These two equations, (6) and (7), follow directly from the diagram Fig. 9 herewith, where X is the time displacement of the resultant ampere conductors against the axis 0-1, which represents the time when the ampere conductors of set No. 1 are a maximum and set No. 2 are zero. Substituting (6) and (7) into (5), the resultant bar current is found to be:

$$i_{b\beta} = I_b (\cos x \cos \beta + \sin x \sin \beta) \quad (8)$$

The same general law holds true for the voltages generated in the bars. The generated voltage minus the ohmic drop in the bars gives the "free voltage." This "free voltage" between the ends 2-3 of the bars 2-1 and 3-1 and between the ends 1-4 of

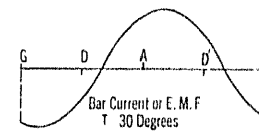


FIG. 13

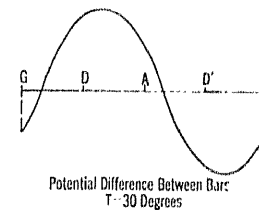


FIG. 14

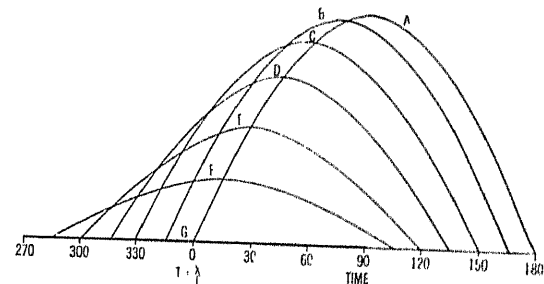


FIG. 15—CURVES SHOWING RELATIVE MAGNITUDES OF CURRENTS IN RING 2 AT VARIOUS INSTANCES OF TIME

the same bars must be equal to the ohmic drop appearing across these points due to the ring currents. As the bar currents as well as the generated bar voltages follow the same law, the "free voltage" which appears across the points 1-2 and 3-4 can be considered as the differential of Equation (8) when the latter is multiplied with a constant taking care of the ohmic drop. The potential difference referred to above is, therefore, given by:

$$dE = K (\sin x \cos \beta - \cos x \sin \beta) d\beta \quad (9)$$

The current flowing in ring No. 2 due to ampere-conductor set No. 1 is:

$$i_{r\beta'} = I_b \cos x \left(-\frac{Z}{\pi} \right) \sin \beta \quad (10)$$

which follows from Equation (3) of the paper and Equation (6) of this discussion.

In the same manner the current in ring 2 due to ampere-conductor set 2 follows from Equation (16) of the paper and Equation (7) of the discussion:

$$i_{r_{2\beta}} = I_b \cdot \frac{Z}{\pi} \sin x (1 - \cos \beta) \quad (11)$$

The resultant current in ring 2 is the sum of (10) and (11) and is given by:

$$i_{r_{2\beta}} = I_b \cdot \frac{Z}{\pi} \{ \sin x (1 - \cos \beta) + \cos x \sin \beta \} \quad (12)$$

In the same manner the resultant current in ring 1 is found to be:

$$i_{r_{1\beta}} = I_b \cdot \frac{Z}{\pi} \{ \sin x (1 + \cos \beta) - \cos x \sin \beta \} \quad (13)$$

The difference between these currents gives:

$$i_{r_{\beta}} = 2 I_b \cdot \frac{Z}{\pi} \{ \sin x \cos \beta - \cos x \sin \beta \} \quad (14)$$

This current multiplied by the ohmic resistance $R \cdot d\beta$ for the infinitely small length of the ring covered by an angle $d\beta$ gives Equation (15) for the ohmic drop in the rings over a section located at point β , that is, the ohmic drop of ring sections 2-3 and 1-4 of the rings 1 and 2.

$$= 2 \frac{Z}{\pi} I_b \{ \sin x \cos \beta - \cos x \sin \beta \} d\beta \quad (15)$$

It will be seen that this is exactly the same law as Equation (9), which represents the potential differences of points 2-3 and 1-4 due to the difference of generated voltage minus the ohmic drop

for bars 1-2 and 3-4. Consequently the second Kirchhoff law has been satisfied,—the sum of all the e. m. f. in the circuits 1-2 and 3-4 is zero. It has, therefore, been shown that for an infinite number of bars the assumption made in my paper of sine-shape current distribution in the bars is correct provided the rotating magnetic field has sine-shape distribution in space.

If, however, the number of bars becomes very small, then, as Mr. Hellmund has shown, the distribution of currents no longer follows a sine law. Experience with standard squirrel-cage rotors has shown that relations derived for an infinite number of bars give results close enough to be applied to a standard squirrel cage having a number of bars such as is usually found in practice, that is, approximately 10 or more bars per pole. It is justifiable to conclude that similar relations exist for squirrel cages with split rings.

The following is a brief description of a graphical solution:

Fig. 10 herewith shows for the time intervals $t = 0$, $t = 30$, $t = 60$, $t = 90$, the current distribution as determined in my paper for the bars and ring No. 2.

Fig. 11 herewith shows the current distribution as determined in my paper for rings 1 and 2 at a time $t = 30$ deg. The difference between these current distributions is given in Fig. 12 herewith, which is a sine-shaped curve and is 90 deg. displaced from the assumed current and voltage distribution of the bars shown by Fig. 13 herewith. But the potential difference between the ends of the bars due to the generated voltages and ohmic drop in the bars is the differential of curve Fig. 13 and follows a sine function as per Fig. 14, which is 90 deg. displaced against curve Fig. 13. Consequently it is co-phasal with the curve of Fig. 12. It follows that this graphical method leads to the same results found above by mathematics, that is, the current distribution as found in my paper for an infinitely large number of bars satisfies the Kirchhoff laws.

Excitation Systems

Their Influence on Short Circuits and Maximum Power

BY R. E. DOHERTY*

Member, A. I. E. E.

Synopsis.—Since 1920, when the general subject of excitation systems was reviewed at the White Sulphur Springs Convention, two important problems regarding these systems have arisen: One relates to the required excitation characteristics during system disturbances, and the other to the characteristics which are necessary in order to increase the maximum power above the steady state or static limit—i. e., in order to operate the synchronous machines under the condition of dynamic stability.

With respect to the former problem, the advantages and disadvantages of quick response excitation are considered. Such excitation tends, of course, to hold up the voltage during system disturbances, and is thus advantageous. However, it also increases the short-circuit current which circuit breakers must interrupt. The general trend in installing such systems is, therefore, in the direction of requiring larger circuit breakers. Such an excitation system is justified in many cases, and, indeed, it is essential in some. The extent to which the quickness of response and the maximum value of the excitation voltage are carried, is a question which, at present, should be settled by the conditions of the particular case.

As to increasing power limits, results are given which are very promising with respect not only to long distance transmission, but also to power systems which have approached the power limit as determined by the condition of present normal operation. A new regulator, unique in its operating characteristic, has been developed which makes it possible to sustain stable operation under the condi-

tion of dynamic stability, thus increasing the maximum power by taking advantage of a heretofore unexploited range of operation of synchronous machines. Comparative test results are given for different types of regulators. The new regulator alone showed extraordinary gain, giving an increase of maximum power from a steady state (steady-field excitation) value of 110 kw., to a maximum of 415 kw., on a system comprising a synchronous generator supplying power directly to a synchronous motor. This shows the extent of improvement obtainable in the machines themselves.

With an artificial 500-mile straightaway transmission line between the machines, a maximum power (received at the motor) equal to 90 per cent of the "infinite bus" value was obtained. The infinite bus value was 61 kw., 55 kw. was obtained, 44 kw. being the steady state power limit.

The excitation system, as controlled by the new regulator, provides a component of excitation voltage which is at all instants equal to the $i r$ drop in the field circuit during the necessary small oscillation under dynamic stability. The $i r$ drop is therefore compensated, the characteristic of the regulator being to introduce the effect of negative resistance. And with zero effective field resistance, the maximum power corresponds to the condition of constant flux linkages—the power under that condition is greatly increased above the constant field current value. This condition is approached by the new regulator.

* * * * *

INTRODUCTION

THE subject of excitation systems was reviewed comprehensively by several authors at the Summer Convention in 1920.¹⁻⁶ Interest has been renewed in this subject in the last few years by the new problems which have arisen in connection with power transmission. Two predominating facts have changed profoundly the general aspect of power transmission: One is the rapidly rising demand for increased reliability of service, and the other, the radical increase in the load per transmission circuit and in the specific loading of synchronous machines. And these facts have given rise to two corresponding problems in excitation systems. One related to the quick and adequate application of excitation voltage under the condition of sudden disturbances, such as short circuits, in order to reduce to a minimum the drop in line voltage—thus preventing to the greatest practicable extent the loss of load either from relay operation or from actual breakdown of motors or synchronous machines. The other relates to the possibility of increasing the maximum power above the generally recognized steady state or "static" limit—by operation under *dynamic*

stability, that is, stability which depends upon motion. Instances: A spinning top, a staff balanced by a juggler, a bicycle in motion. Any tendency to fall gives rise to restoring forces. These may be inherent, as in the case of the top, or may be impressed by an external agency, as in the case of the staff or a slowly moving bicycle. But in either case the tendency to fall initiates the restoration. Moreover, in dynamic stability the play of these opposing forces is continuous. In the case of the synchronous machine operating under the condition of dynamic stability, the tendency to fall out of step initiates, through the voltage regulator, an appropriate change in excitation, thus providing the restoring forces. It is the purpose to discuss these two problems, and to report certain facts which appear to be steps forward in the solution.

Although the two problems are discussed separately, since in certain fundamental respects they are quite distinct, they are nevertheless related in the important respect that the problem of preserving continuity of service through periods of system disturbance would always be present, regardless of whether the system were normally operating under *static* stability or *dynamic* stability. However, it should be thoroughly appreciated that these two states of operation are fundamentally different, and that excitation systems which are satisfactory for the one may be altogether inadequate for the other.

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1. For all numerical references see Bibliography.

Presented at the A. I. E. E. Regional Meeting, St. Louis, Mo., March 7-9, 1928.

With reference to the earlier work on excitation systems in connection with power transmission, two possible means for obtaining improved control of the excitation were suggested by the author at the Seattle Convention in 1925.⁷ One was the use of a series exciter in the excitation circuit, in order to obtain immediate response in increased excitation voltage on the occasion of any sudden change in the electrical condition of the synchronous machine—in other words, to obtain an equivalent negative resistance in the field circuit. This, of course, would lengthen the duration of the transient, *i. e.*, tend to sustain the spontaneously increased alternator field current. The other suggestion was the use of a mercury arc rectifier as an adjunct in the excitation circuit. This would give immediate change in alternator field current in proportion to the change in armature current. Tests showed that with this scheme it was possible to operate above the steady state power limit. Further investigation has shown that there are equally effective and simpler means for both cases: One relates to the problem of short circuits, and the other to the problem of increasing the maximum power by operation under dynamic stability. These will now be considered.

EXCITATION CONTROL DURING SYSTEM DISTURBANCES

The value of what has been termed "quick-response" or "high-speed" excitation, in connection with system disturbances, has been widely discussed.⁸⁻¹² There are, however, important points which warrant further emphasis. These relate to the rate of application of excitation, the maximum value of excitation voltage, the effect of this on short circuit currents, and also to the voltage regulator's role.

In the first place, what is quick-response excitation? When does the response of an exciter cease to be sluggish, and become quick? The term refers, of course, to exciters whose rates of magnetic build-up and build-down are higher than those ordinarily obtained with standard machines. The rates obtained with the latter over a wide range† are, say, from 15 or 20 volts per second to perhaps 250 volts per second in the case of 250 volt exciters, and half those values for 125 volt exciters, the range depending upon such factors as the volume (the $d^2 l$), and the speed of the exciter, saturation, character of the iron, etc. It would thus be somewhat venturesome to attempt to set a dividing line between high and low rates. However, anyone would probably agree that 25 volts per second is a low rate, and 1000 volts per second is a high rate. The width of the questionable zone depends, in the present state of definition, upon individual notions. But for the purpose of this discussion, we may very reasonably regard as quick-response excitation those cases where extraordinary means are employed to obtain rates of voltage change, both increase and decrease, unattainable in standard shunt or compound-wound exciters.

†Data in this connection will be given in a forthcoming paper in the *General Electric Review* by Mr. H. W. Washburn.

The extraordinary means referred to are, of course, familiar to all designing engineers, and include a number of schemes, such as special exciter design; the use of a series resistance in the shunt-field circuit, and impressing a correspondingly higher voltage; or, impressing a much higher voltage on the exciter field than corresponds, by Ohm's law, to the desired shunt-field current. Whether the latter, for instance, is accomplished by paralleling the field coils and impressing the given voltage, or by rewinding the coils for series connection, with the same amount of copper but with an appropriately smaller number of turns, and impressing the given voltage on the series circuit, the result is the same—namely, an accelerated voltage change. Such schemes for obtaining a high rate of d-c. voltage have been used for years,¹³ ever since applications have been encountered which required a more rapid change in excitation voltage than could be obtained by standard machines. Quick-response excitation, as well as certain means of obtaining it, is not something which has recently come upon us as a new phenomenon.

Merely an additional application has arisen. If the line voltage drops, loaded motors may break down, the generators may fall out of step, and other disagreeable things may occur. If the drop in voltage takes place slowly, as occasioned, for instance, by a gradual application of load, the required rate of increase in excitation to prevent a critical dip in the voltage would be correspondingly low. However, if the drop is sudden—as produced by a partial short circuit—any possible advantage to be had from increasing the excitation voltage would be accomplished only by increasing it quickly. Thus, with the growth in the load per transmission circuit and, at the same time, a growing demand for greater reliability of service, it has become desirable and, in some cases, necessary to extend the use of quick-response excitation, formerly confined chiefly to special cases of industrial application in the field of large power transmission systems.

Published literature has brought out clearly the foregoing fact, that the quick application of excitation voltage on the occasion of a short circuit will decrease the chance of system breakdown—because it tends to hold the voltage up; but, as already mentioned, there are other important aspects of the subject which deserve further emphasis.

One of those aspects is that there are certain important details which are essential to an *effective* application of quick response excitation systems. The purpose being to reduce to a minimum the drop in voltage due to a sudden disturbance, it is clearly desirable for certain practical cases to have not merely a relatively rapid increase in excitation voltage, but the highest practicable rate and a relatively high value to which the excitation voltage can build up. For instance, a practical case of 250-volt normal excitation might require 5000 volts per second or higher, instead of 500, and a maximum value ("high ceiling") of say

1000 volts, instead of 300 or 400. These points have been discussed by Mr. D. M. Jones in a recent issue of the *General Electric Review*.¹²

There are thus special applications in which, for optimum results, these features must be given due consideration.

But such features can be carried too far. The consequent increase in short-circuit current may create equally difficult problems. Indeed, the purpose of quick response excitation may be stated in terms of short-circuit current. Thus, reducing the voltage drop during the period of short circuit to a minimum, is equivalent to increasing to a maximum the value of the short-circuit current which the circuit breaker must open. Until the last few years the problem had been to reduce the short circuit current, but now, in these instances at least, the tendency is to increase it. In many cases this would not entail difficult switching problems, but there are some in which it would. Therefore, the suggestion is offered that the general trend has reversed to the direction of sustaining high short-circuit currents; and that in addition to both the proposed shorter time interval between the short circuit and the opening of the switch, and the radical increases in the generator capacity connected to a single bus, this is heading toward difficult switching conditions. Thus in the application of such excitation systems this general trend should be considered in true perspective.

The voltage regulator's place in this picture should be mentioned. So far as the particular function is concerned (of reducing the voltage drop during short circuit to a minimum), the *foremost* requirement of the regulator is that it should close its contacts immediately after short circuit, and keep them closed until the maximum desired excitation voltage appears across the field-collector rings of the synchronous machine; though there are other requirements, naturally. This fact, it seems, is generally recognized; and such commercial regulators generally are available. There are, however, other very important regulator functions and required characteristics which do not appear to be generally understood, particularly in connection with the problem of dynamic stability. These will be discussed later on.

To sum up the more important points regarding the influence of the excitation system during system disturbances: Quick-response excitation is highly desirable from the standpoint of reducing to a minimum the voltage drop during short circuit; and to this end, much higher rates and much higher values of excitation voltage are required, in certain practical cases, than had formerly been considered in quick-response systems. The definite present trend, however, in installing quick-response excitation systems is in the direction of increasing the duty on circuit breakers; and as a question of broad policy this should be fully considered. With respect to the voltage regulator, its foremost requirement in connection with short circuits is that it should

promptly close the contacts and keep them closed until the desired d-c. voltage across the field-collector rings has been attained. Regulators which will do this generally are available.

EXCITATION CONTROL FOR DYNAMIC STABILITY

Formerly, voltage regulation, line loss, and short circuits were the chief limitations considered in power transmission systems. During recent years another limitation, maximum power, has become very important. Under economic pressure, the load per transmission circuit has been increased until the maximum power which it is possible to transmit under existing conditions and practise, has been approached; indeed, in certain proposed power developments it has been exceeded. This has occasioned active investigation to increase the maximum power above the steady state, or static power limit.

Experience and early study regarding the possibilities in the design of the synchronous machine showed that although a gain in maximum power could be made in this way, it was nevertheless a moderate one, considering the economic limitations involved and the subject sought.⁷ Even if such gains were made available as they have been—there would, nevertheless, still remain in these machines the latent possibilities of increased maximum power beyond the static limit. And, as early studies indicated, it was these possibilities which could be rendered available by a proper excitation system. This view was presented at Seattle in 1925, together with evidence that operation beyond the static limit could be obtained by proper excitation control.

With this fact established, intensive investigations were made of various forms of excitation systems with the object of increasing the gain and simplifying the circuits. Analysis and tests have definitely established three very important points. One point is that the factors of mechanical inertia, electrical transients, and damping afford a sufficient time element to make it possible to *sustain* operation under *dynamic* stability far beyond the *static* power limit. As discussed later on, the possibilities in this connection proved to be much more favorable than earlier investigation has indicated. The second point is the very essential part which the voltage regulator plays in this accomplishment. Third, the relatively low rates of change of excitation voltage at which it is possible, with proper regulation, to sustain dynamic stability. Although quick-response excitation may be desirable for many reasons, it is nevertheless a fact that it is possible to sustain dynamic stability with ordinary exciters, using proper regulation. These aspects will now be discussed in detail.

Consider the general nature of the phenomenon in question. It is a familiar fact that when a synchronous motor is supplied with power from a synchronous generator, either from a common bus or through an

intervening reactance, there is a definite maximum power in either case, which can be transmitted at normal voltage under steady field conditions. Beyond this limit, generally referred to as the steady state or static power limit, the machines break apart.

It is also a fact that considerably more power can be transmitted by the same machines, over the same circuits, provided that the field excitation of the machines, instead of being held steady, is properly varied in accordance with the demands from moment to moment. Under this condition, as explained in Mr. Nickle's paper, the machines are, at each moment, either actually drifting further apart in phase with a consequent drop in voltage, or nearer together in phase with a consequent rise in voltage. That is, with a constant shaft load under such conditions of operation, there are sets of critical values of terminal voltage, field excitation, and space phase position, at which the electrical power input is just sufficient to supply the motor losses and the mechanical load; and on either side of this critical and sensitive balance, the tendency, *if the system were left to itself with no impressed change in field excitation*, would be either to fall apart with decreasing voltage and decreasing useful power input, or to fall close in phase with increasing voltage and increasing power input. Under these conditions the system is inherently unstable. But with proper control of the impressed excitation voltage, dynamic stability can be maintained, and the maximum power thus increased.

Now it is a well-known fact that the alternator field current tends inherently to adjust itself to maintain constant magnetic linkages in the field circuit.⁷ This tendency is greater, the lower the resistance of that circuit; and in the limit, if the resistance were zero, the linkages would thus be maintained absolutely constant. Stated in other words, with zero resistance in the field circuit the effect of armature reaction on the field would be completely compensated.

The purposes of the mercury arc and the series exciter schemes, already referred to, are fully discussed in the literature.⁷ The former effects partial compensation by changing the alternator field current in proportion to the line current, the latter, by introducing a component of excitation voltage which is at all moments proportional to field current, thus being, in effect, a negative resistance. With proper characteristics it should be possible in this way to introduce a negative resistance equal to the positive (*i. e.*, ohmic) resistance, and thus obtain the beneficial effects of zero resistance as discussed above. Although the series exciter has this advantage, it has some disadvantage in that it introduces an inductance (the exciting inductance of the exciter) in the external field circuit, thus increasing the transient reactance of the alternator and, therefore, decreasing the maximum power. Moreover, it would involve a somewhat complicated control. So, although both the mercury arc and the series exciter may yet find application in this connection, this investigation

has shown that means are available which now appear much more promising.

The effect of negative resistance in the alternator field can be obtained by a special vibrating type regulator, actuated from the a-c. line voltage, and controlling an ordinary exciter. The inherent relationships between displacement angle, line voltage, field current, etc., during the necessary oscillatory motion in dynamic stability, are such that a component of excitation voltage proportional to the varying field current can be impressed by the above means, provided the regulator has proper characteristics. The above relationships are roughly indicated in Fig. 1. The oscillations may not be periodic; and the magnitude of variations would normally be less than indicated. But some oscillation must nevertheless be present in dynamic stability. The problem is to obtain an excitation system which will apply a voltage as shown as curve *d* in Fig. 1, that

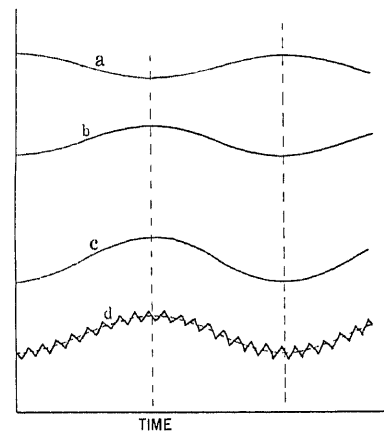


FIG. 1—PHASE RELATIONSHIPS DURING ANGULAR OSCILLATION OF AN ALTERNATOR

- (a) Envelope of a-c. voltage
- (b) Angular displacement
- (c) Field current
- (d) Exciter voltage

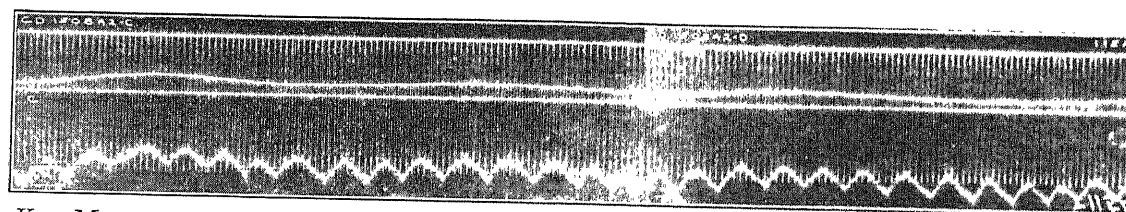
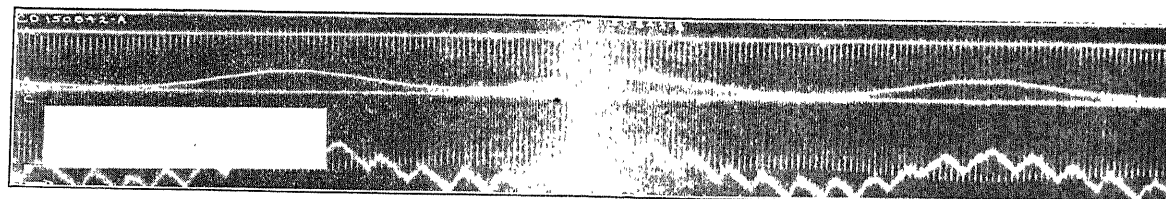
is, one which is in time phase with, and proportional to, the variable field current. It would thus constitute in effect a negative resistance. If the excitation voltage in this way were made equal to the ir drop at all instants, the objective of equivalent zero resistance would be attained.

A regulator has been developed by Mr. C. A. Nickle which practically accomplishes this and, therefore, makes it possible to obtain large gains in maximum power above the steady-state limit: Its characteristics are referred to later, and are discussed in detail by Nickle and Carothers in a companion paper. Oscillograms of the line voltage, field current, and excitation voltage under dynamic stability are shown in Figs. 2A and 2B. (The record of field-current oscillations was magnified by inserting a constant d-c. component in the oscillograph circuit in opposition to that due to the field current.) In 2A a relatively large, damped oscillation is shown under the condition of operation at

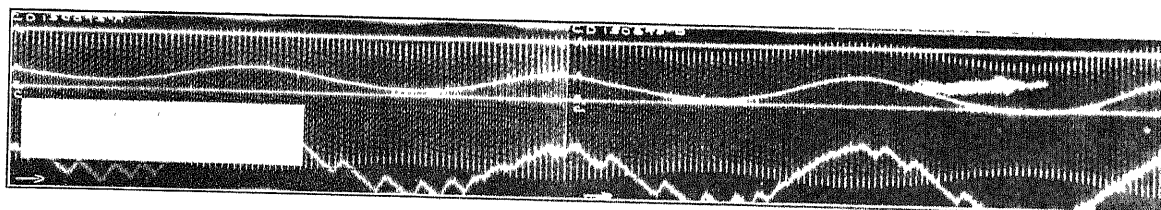
405 kw., the steady-state power limit being 110 kw. The test set-up is shown in Fig. 3. Fig. 2B shows a cumulative oscillation and breakout. In this case the power was only 370 kw., but the regulator was not adjusted at the optimum setting. The negative resistance was too large, thus introducing negative damping and consequent cumulative oscillation. But in both cases it will be noted that the variation of the average (that is, taking the average of the ripples)

versa. And since the field current variation is also of a similar, but reversed, form with respect to the a-c. voltage variation, it means that the exciter voltage will substantially follow the field current, even for irregular variations. Thus, in general, the effect of negative resistance is afforded by the regulator.

However, negative resistance is not an unmitigated advantage. It affords increased synchronizing power, but does so at the expense of positive damping. Damp-



(A) 405 Kw. MAXIMUM POWER OBTAINED WITH ADJUSTMENT OF REGULATOR TO GIVE OPTIMUM VALUE OF EQUIVALENT NEGATIVE RESISTANCE



(B) CUMULATIVE OSCILLATION AND BREAK-OUT AT 370 KW. OBTAINED WITH REGULATOR ADJUSTMENT TO GIVE TOO LARGE NEGATIVE RESISTANCE

FIG. 2—OSCILLOGRAMS OF MAXIMUM POWER WITH A TYPE A REGULATOR. SET-UP SHOWN IN FIG. 3. STEADY STATE POWER LIMIT, 110 KW.

Curve A— T S field current 1 mm = 0.3 amperes (true zero line displaced 50.5 mm. above reference line B_0 see text).
Curve B—Exciter armature voltage 1 mm. = 3.09 volts as measured from zero line A_0
Curve C—A. C. line voltage 1 mm. = 4.87 volts. P. T. Ratio = 20:1.

exciter voltage is substantially in phase with the field current variation; and hence a large component is exactly in phase, thus providing the effect of negative resistance.

But even if the terminal voltage variations are irregular, the regulator will cause the variation of the average exciter voltage to conform substantially to the same pattern, only reversed. That is, the exciter voltage will be up when the a-c. voltage is down, and vice

ing due to the field winding is a very important factor in dynamic stability. As the effect of ohmic resistance is gradually eliminated by the foregoing means, the synchronizing torque is correspondingly increased,¹⁷ but the net damping is decreased; and when the exciter voltage more than compensates the $i r$ drop, negative damping results. That is, under this condition any oscillation will cumulate and, unless other damping devices are present, will cause breakout. This is

illustrated in Fig. 2B. The value of the negative resistance is fixed by regulator adjustment, as explained by Nickle and Carothers.

An amortisseur winding should thus be of some advantage when the machine is operating near the point of maximum power.

The phase relations of the various components of excitation voltage should be further considered. The period of oscillation is of the order of 1 sec.—*i. e.*, of a

frequency of one cycle per second. Since $\frac{L}{R}$ of the field for this condition is of the order of 2 to 3 sec.,

$\frac{X}{R}$ at one cycle per second would be of the order of

12 to 18. It follows that the alternating component of field current due to the pulsating exciter voltage will lag by approximately 90 deg. Hence, referring to Fig. 1, we may say for the purpose of rough illustration

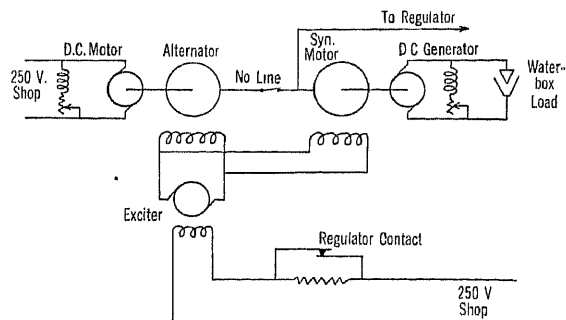


FIG. 3—TEST SET-UP WITHOUT TRANSMISSION LINE

Machine Ratings

Alternator and motor TS-6-435-1200-4000/2300 volts
 D-c. motor and generator MPC-6-300-1200-250/275 volts
 Exciter MP-4-17-700-250 volt 68 amperes
 Synchronous reactance (without saturation) of generator = 46 ohms
 $W R^2$ of rotor (total) = 2880 lb.-ft.²

that that component of alternating exciter voltage which is in phase with the given alternating component of field current (in phase with the angular position), produces a component of field current and, therefore, a torque, in time quadrature. This torque is thus in phase with the motion and is, therefore, negative damping, tending to increase the motion. It opposes the positive damping represented by the alternating component of $i r$ drop, and when it is in excess of the latter, cumulative oscillations follow.

The other component of exciter voltage which is in time quadrature with the field current, produces a component of field current in phase opposition to the given field current. It thus decreases the synchronizing torque.

The foregoing relations are of course not strictly true, but they will serve to illustrate the general nature of the effect of impressing different components of excitation voltage, and to show how regulators with different operating characteristics may produce very different results of maximum power and stability.

The point of view of evaluating the effect of the exciter and regulator in terms of equivalent circuit constants in the field can be developed further. As already explained, that component of exciter voltage which is in phase with the field current gives the effect of negative resistance. Now the component which is in time quadrature (lagging), gives the effect of an inductance in the circuit—*i. e.*, equivalent to increasing the transient reactance. This component is undesirable, at least so far as the maximum power is concerned. It follows that a component in phase opposition to the latter would give the effect of negative reactance, and would thus be advantageous.

With the new regulator, which impresses an exciter voltage in phase opposition with the line voltage variation, and therefore in phase with the field current variation, operation under dynamic stability was carried far beyond the steady state or static power limit—in one particular test among many, under the set-up of Fig. 3, to over 4 times the static limit, *i. e.*, to 450 kw.

Digressing for a moment in retrospect, the author's view regarding one aspect of this problem has changed. In the earlier stages of this general investigation⁷⁻¹¹ when a study was being made to find means for compensating the effects of armature reaction on the field, it appeared that any scheme involving a vibrating regulator actuated by the a-c. voltage, and controlling an exciter, would be too sluggish, and that therefore some other scheme, such as the mercury arc and series exciter, would be necessary. Subsequent investigations, however, have shown that on account of the inherent character of the relationships between the line voltage, angle, and field current, as shown in Figs. 1 and 2, the excitation voltage rate does not have to be extremely high in order to effect such a compensation. Taking advantage of the time element afforded by inertia and damping, the average exciter voltage can be made to vary, up and down, in time phase opposition with the line voltage variation, and, therefore, approximately in time phase with the field current—provided the regulator gives prompt and appropriate response in excitation voltage. In other words, more can be accomplished by a vibrating regulator than had been anticipated in the early stages of the investigation.

The foregoing discussion has centered largely about the regulator and the alternator characteristics. It may be asked, what effect has the exciter voltage build-up rate upon the maximum power which can be transmitted under dynamic stability?¹⁶ Such operation obviously depends in a decisive way both upon the characteristics of automatic voltage regulators, and the quickness of response of the excitation source. An excitation system is a composite, and not a number of independent elements. An exciter can obviously do no more than react, in accordance with its inherent characteristics, to the conditions which are imposed upon it by the regulator and the connected circuits;

while the regulator can only control the particular exciter, whatever it may be, according to the regulator's inherent characteristics, and as it is influenced by the controlling and controlled circuits. An excitation system is thus like most other systems—if all components are not properly constituted and coordinated, it will not function efficiently.

It happens, however, that the exciter voltage rates obtainable from standard exciters are high enough to sustain dynamic stability, as shown under the heading, TESTS. The range of rates of voltage build-up of standard exciters has been given under EXCITATION CONTROL DURING SYSTEM DISTURBANCES. This does not mean that quick-response excitation should not be used if its use is desirable for some other reason—say to apply excitation quickly on the occasion of a system disturbance. If the regulator has the right characteristics, it can apply quick-response excitation as readily as it can apply the excitation from standard exciters, and obtain the same maximum power, as shown later.

A very definite distinction, however, must be drawn between the rate of variation, up and down, of exciter

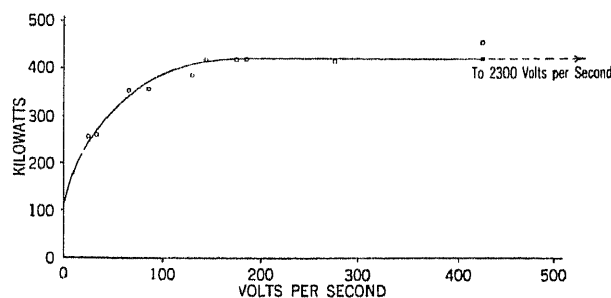


FIG. 4—MAXIMUM POWER AS A FUNCTION OF THE EXCITER VOLTAGE BUILD-UP RATE, FOR THE TEST SET-UP OF FIG. 3, USING TYPE A REGULATOR

voltage as the contacts close and open, on the one hand, and the consequent rate at which the average excitation voltage changes, on the other. This difference may be very great depending upon the type of regulator.

The question regarding the relative influence of regulators and of the voltage rate of exciters on the maximum power which can be transmitted under dynamic stability will now be answered by tests.

TESTS

One particular test set-up, among a large number, is shown in Fig. 3, including the ratings of the machines. The tests were run at about half voltage in order not to overload the d-c. generators under the condition of the large increase in power. Even at half voltage on the synchronous machines, the d-c. output (normal voltage) at maximum power was more than normal. The alternator fields were wound for 250-volt excitation. The exciter was a 250-volt machine, operating at 50 volts at zero power, 200 volts at the ultimate maximum power—*i. e.*, at 415 kw., (Fig. 4).

There are four principal voltage regulators with which comprehensive maximum power tests were made,

including tests at different exciter voltage rates. Others were tested, but not so comprehensively. The four types are:

A. Original model of the regulator embodying the new principle. This will be referred to as type A in the following discussion.

B. New commercial form embodying, in the main, the characteristic features of the original model. This will be referred to as type B.

C. Older commercial form with d-c. coil, which will be designated as type C.

D. The usual commercial form without d-c. coil, which will be designated as type D.

In tests with type A regulator and with an exciter voltage build-up rate of 24 volts per sec. (as measured by oscillograph at the exciter terminals under the actual condition of maximum power), a value of power equal to twice the fixed-field, or steady-state value, was obtained; and with a measured build-up rate of 142 volts per sec., (obtained by changing connections in the exciter field circuit), 3.75 times the fixed-field value was obtained. The average exciter voltage at maximum power was 200 volts. Further increase in exciter rate up to approximately 2300 volts per sec. gave no appreciable further increase in power. When the exciter rate was increased to approximately 3000 volts per sec., the system became unstable. The maximum of 415 kw. could no longer be held. No satisfactory explanation of this appears at present. Now 24 volts per sec. and 142 volts per sec. would not be termed quick-response excitation, even on a 125-volt exciter; but here it was a 250-volt exciter. Thus, those rates would correspond to 12 volts per sec. and 71 volts per sec. on a 125-volt exciter. It was the most sluggish exciter which had been found.

The only interpretation which the author has been able to make of those facts is that the regulator played a decisive part in obtaining the improvement in power limits, and that quick-response excitation had nothing to do with it, because quick-response excitation was not used in obtaining the results; and moreover because, when the rate of exciter build-up was increased to a high rate, no further improvement was found. Fig. 4 shows the curve relating the measured exciter voltage rate and maximum power, as obtained in the test set-up of Fig. 3.* The build-down rate was of the same order as the build-up rate. A different series of tests on the same apparatus, but showing about 5 per cent greater maximum power is shown by Nickle and Carothers. A more detailed reference will be made later to the exciter build-up rate and its relation to maximum power.

Another test under the conditions of Fig. 3 was taken, using type B regulator. The maximum power obtained was 385 kw., *i. e.*, 3.5 times the steady-state limit; and

*This may answer satisfactorily the question raised in the literature, reference 16.

hunting did not begin until a load of 250 kw. was passed.

The test set-up shown in Fig. 5 includes an artificial 500-mile transmission line between the motor and generator, the reactance of the line being approximately 1.5 times the synchronous reactance (46 ohms) of the generator, the generator and motor being duplicate machines. The machines were each regulated at 2240 volts. In this case, the static power limit was 44 kw., the infinite bus value being 61 kw. With the type A regulator, 55 kw. was transmitted, *i. e.*, received

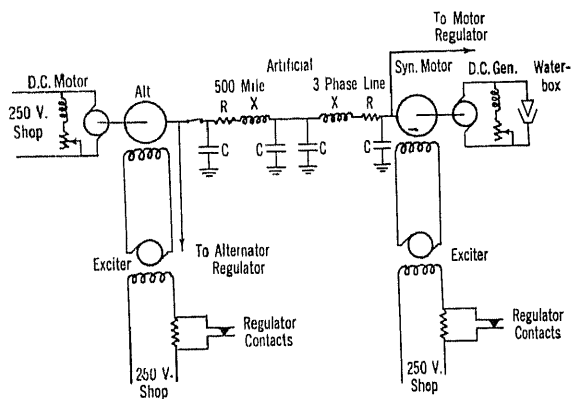


FIG. 5 -- TEST SET-UP WITH ARTIFICIAL 500 MILE TRANSMISSION LINE

Machine ratings

Alternator and motor TS-6-435-1200-4000/2300 volts

D. C. motor and generator MPC-6-300-1200-250/275 volts

Exciters MP-4-17-700-250 volts

$X = 35.5$ ohms

$R = 5.0$ ohms

$C = 3.75$ mf.

at the motor. This is 90 per cent of the infinite-bus value. This result was obtained with two different exciter rates, namely, 500 and 250 volts per second. The average exciter voltage at the maximum power was 66 volts.

The increase in maximum power was naturally less here than in the case of Fig. 3, because the line impedance drop is, in a sense, an unregulated factor in the situation; that is, since the voltage is regulated at the machine terminals, the machine impedance drops only are corrected. For instance, if the voltage at the middle of the line, instead of at the ends, were regulated at normal value, the increase in power would be much greater. The voltage at the machine terminals would then be greater, since in that case the line reactance would in a sense be equivalent to an addition to the synchronous reactance under the condition of Fig. 3.

Referring again to the tests, a number of regulators has been tried in various factory tests using the same machines and circuits. None of the former commercial models in these comparative tests could approach the maximum power obtainable under dynamic stability with the new model. In certain early factory tests with 5-kv-a. machines, the new regulator alone (type A, and type B) made possible a decisive increase in maximum power above the steady-state limit. The maximum power obtained with these types was 11.0

kw., the steady-state limit being approximately 7.0 kw.,† and the infinite-bus value, calculated, was 12 kw. With the other regulators, including types C and D, and also a commutator type, the synchronous machines broke apart at substantially the steady-state limit of power.

In later tests, however, in which larger machines, with relatively larger inertia and damping, were used, it was possible with commercial regulators to obtain an increase above the steady-state limit. In the tests of Fig. 3 (no impedance between machines), in which the new regulator type A gave 3.75 times that limit, with practically no hunting until 3.5 was passed, type D without d-c. coil gave only 1.75 to 2.0 times that limit with serious hunting. In the latter case, hunting began as soon as the steady-state limit was passed, in spite of the most favorable adjustment, and became progressively worse with increase in load, hunting out of step at the above values of power. With the new commercial regulator type B, however, hunting began at about 2.5, and at this value the stability was comparable with that of the commercial type D just after passing the steady-state limit, *i. e.*, at 1.0. In the case of the older commercial type with d-c. coil, (type C), only a small increase was obtained. The machines hunted out of step soon after steady state was passed. Fig. 6 shows the results for all four cases, giving the maximum power which could be held in synchronism. Fig. 7 gives the same results with an indication of the extent and character of hunting.

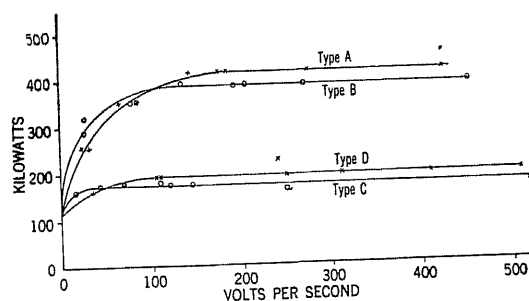


FIG. 6—MAXIMUM POWER AS A FUNCTION OF THE EXCITER VOLTAGE BUILD-UP RATE FOR THE TEST SET-UP OF FIG. 3, USING THE DIFFERENT TYPES OF REGULATORS

Dynamic stability can be sustained also by hand juggling of the exciter rheostats. With rheostats and field-circuit connections such that the exciter rate would be 500 volts per sec. if all resistance were suddenly cut-out, it was possible to sustain over twice the steady-state value of power by hand control of the rheostats. Watching the line voltmeter, the field rheostat was shifted back and forth to correct for the changing voltage. When the voltage started to decrease, the

†These results are given by Messrs. Nickle and Carothers. The test set-up involved two duplicate synchronous machines connected through a line reactance equal to two-thirds of the synchronous reactance of either machine.

rheostat was set by guess at a point to correct the decrease; and as it began to increase, a similar correction was made. It is to be noted that the rheostat was not all cut-out, and all cut-in, as with a regulator; instead, the change in resistance was relatively small. Hence the actual rate of exciter voltage was correspondingly small. Even so, it was possible to obtain an increase of 100 per cent above the steady-state limit by hand juggling.

REGULATOR CHARACTERISTICS

The above results are very interesting in view of the parallel drawn by Messrs. Nickle and Carothers, between such hand control and the inherent action of a regulator—such as the commercial type *D* referred to—which operates on the principle that a definite ratio (time closed) ÷ (time open) exists for each value of a-c. voltage. Thus, these authors show that for small changes in the average exciter voltage, the effective exciter voltage rate from the one voltage to the other is not the rate corresponding to the closed contact, as might at first be supposed, but a much smaller rate—corresponding, much as in hand control, to the relatively small shift from one resistance to another. A small drop in a-c. voltage merely changes the ratio (time closed) to (time open) on the regulator corresponding to the new average resistance necessary for regulation; and the average exciter voltage changes according to a correspondingly slow transient, and not according to the total exciter rate. For illustration, if the above ratio does not change at all, the exciter voltage varies up and down at full exciter rate, but the average value does not change; and if the ratio does change, following a small change in a-c. voltage, it merely sets a new average resistance, *i. e.*, a setting for a new average exciter voltage. But the latter reaches the new value by a relatively slow transient corresponding not to the rate with contacts closed, but merely to the change in average resistance. This is true, in that range of a-c. voltage variation in which the regulator functions normally—*i. e.*, in which the contacts vibrate. This is of the order of ± 10 per cent. If, for instance, the voltage falls below the lower critical value, the contacts close and stay closed; in which case the total exciter rate is the effective rate. But this condition does not exist in operation under dynamic stability. It is thus somewhat analogous to hand juggling, and it is therefore not surprising that the maximum power obtained in test in the two cases was about the same.

The type *A* regulator, however, operates on an entirely different principle—a principle which no other regulator has embodied; and this explains why the increase in maximum power is much greater when it controls the voltage. The principle is: *for a given change in a-c. voltage, the new average exciter voltage for the new condition is reached at a continuous voltage rate equal to the actual total rate of the exciter. This is initiated promptly, and is true for all a-c. voltage changes, small as*

*well as large.** Other regulators may initiate their response promptly, and, moreover, the effective excitation voltage rate may be equal to the rate of the total exciter voltage for *large* changes in a-c. voltage. But no other regulator, to the author's knowledge, affords this equality of voltage rates for relatively small changes in a-c. voltage—such, for instance, as would be encountered normally under the condition we have been considering, namely, dynamic stability. Operating according to the above principle, the new regulator thus causes the average exciter voltage to keep pace with the alternator field current, as in Fig. 1, and therefore provides the effect of negative resistance. (The value of negative resistance is proportional to the resistance in the d-c. coil of the regulator, as explained by Nickle and Carothers. It can thus be easily adjusted for the optimum condition.)

The circumstance that makes it possible for the exciter voltage to follow the field current so closely is that the variations of the latter are relatively slow (of the order of one cycle per second—and this is roughly true for power systems in general) and are also relatively small. For numerical illustration, if the amplitude of variation were, say 10 per cent, of the average field current (which would be a relatively high variation), this would mean that, for complete resistance compensation, the average exciter voltage must vary 10 per cent, and in phase. And the required rate of exciter voltage change would be,

$$\frac{d e}{d t} = \omega e_0 \cos (\omega t + \alpha)$$

where the voltage e_0 is the amplitude of the variation, and ω the corresponding angular velocity. If the amplitude e_0 is 10 per cent—*i. e.*, total variation of ± 10 per cent—and the frequency is one cycle per second, the maximum rate (during the cycle) of the average excitation voltage is,

$$\omega e_0 = 2 \pi \times 10 \text{ per cent} = 62.8 \text{ per cent of the steady component per second.}$$

Hence, assuming that the exciter is operating at 80 per cent of the rated voltage of say 250 volts, the maximum voltage rate would be roughly

$$0.62 \times 0.8 \times 250 = 124 \text{ volts/sec.}$$

This, of course, would be the lowest permissible value of the maximum rate under the assumptions. It will be noted that this is of the order of the lowest voltage rate at which maximum power was attained—Fig. 4.

Thus, summing up the new regulator characteristics, it operates on a unique principle which makes it possible, on account of the relatively slow oscillation in dynamic stability, to impress an excitation voltage substantially in phase with the field current variations, therefore affording the effect of negative resistance, as illustrated in Fig. 2. It will be observed that the phase

*For the detailed treatment of this, see companion paper by Nickle and Carothers, p.957.

displacement between the field current and excitation voltage corresponds to only 2 cycles of a-c. voltage, *i. e.*, about 12 deg., since the cycle of variation corresponds to one second. In other words, the in-phase component is approximately 98 per cent of the total; the quadrature component, only 20 per cent.

Now consider the type *D* regulator in these terms. From the principle of its operation, already discussed,

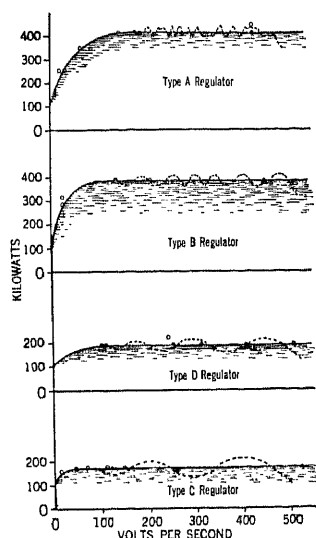


FIG. 7—THE SOLID CURVES ARE THE SAME AS THOSE SHOWN IN FIG. 6

The shading is intended to indicate the intensity and range of hunting. Thus heavy shading indicates serious hunting, and no shading indicates practically stable operation. The dotted line, with time as abscissa, indicates the general character of the oscillation corresponding to imminent break-out

full exciter voltage rate. Hence in an oscillation, and especially a small oscillation, in that range of the voltage variation in which the voltage is changing only slightly, as immediately after the maximum or the minimum, practically no change in the average excitation voltage occurs. And as the variation reaches the larger slopes, the excitation voltage begins to change more rapidly. This means inherently a lag in phase. Thus, unlike the type *A* regulator, here the effect of the regulator and exciter, instead of being a negative resistance, is equivalent to shunting the resistance of the alternator field circuit by an inductance. For any spontaneous change in the field current, the $i r$ drop, due to the added current, is present in the first moment, but gradually disappears as the current is taken by the shunt inductance which has no resistance; and the rate at which the $i r$ drop disappears depends upon the magnitude of the change in the alternator field current. This therefore represents the conditions as outlined for the type *D* regulator. Thus, the exciter voltage is represented by the voltage across the parallel circuit of the inductance and resistance. As such, it must be out of phase with the total current. Fig. 8 shows the actual phase relations under a test in which the conditions were the same as those in Fig. 2, except the type *D* regulator was used instead of the type *A*. It will be noted that the phase displacement between the average excitation voltage and the alternator field current corresponds to about 10 cycles—*i. e.*, about 60 deg. lag. Thus, only 50 per cent is in phase, 86 per cent in quadrature (lagging). This explains why only 190 kw. could be ob-

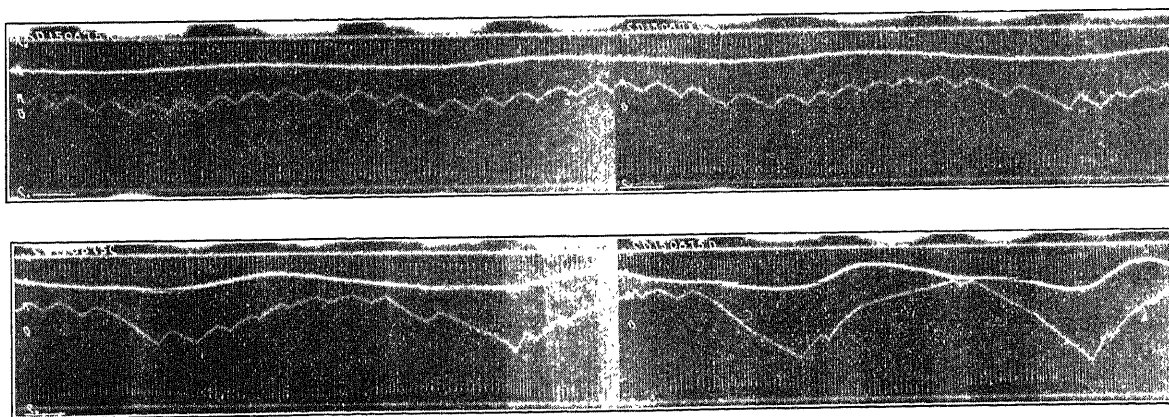


FIG. 8—OSCILLOGRAM OF MAXIMUM POWER TEST WITH A TYPE *D* REGULATOR ADJUSTED FOR OPTIMUM CONDITIONS. SET-UP SHOWN IN FIG. 3. STEADY STATE POWER LIMIT, 110 KW. 190 KW. MAXIMUM POWER OBTAINED

Curve A—Exciter armature voltage 1 mm. = 3.43 volts (as measured from zero line A_0)
 Curve B—A-c. line voltage 1 mm. = 5 volts. P T. Ratio = 20:1
 Curve C—T S field current 1 mm. = 0.135 amperes (true zero line displaced 0.09 mm. above reference line C_0)

it is clear that for a given change in a-c. voltage, a new setting of average resistance, corresponding to the new, anticipated average excitation voltage, is instantly effected, and a transient of the average excitation voltage is started, the rate of the transient depending upon the magnitude of the change. For a small change the rate is very low; for a large change, it approaches the

tained instead of 405 kw. in Fig. 2. Fig. 8 shows the conditions at the maximum power, just preceding break-out. The regulator was adjusted at its optimum setting.

In the case of type *C*, since it also is not so responsive to small voltage changes, it naturally must also permit large angular and voltage oscillations, just as soon as

the dynamic state of operation is entered; and thus the increase in maximum power should also be less than that of the types *A* and *B*, and the hunting more severe. And this is what actually happens, as indicated in Fig. 7. While this regulator serves well the general purpose for which it was designed and for which it has been and is being widely used, it is nevertheless seriously handicapped—even somewhat more than the type *D*—in connection with operation under dynamic stability. For this state of operation, a new regulator with a new principle of operation is required, such as types *A* and *B*.

SUMMARY AND INTERPRETATION OF CONCLUSIONS

What interpretation is to be placed on the foregoing discussion and facts? Should quick-response excitation systems be always used, and how "quick" should the response be? What element in the excitation system has made possible the large gains in maximum power reported in the paper? What is the significance of the gains regarding the future of power transmission?

Two predominating facts in the field of power transmission have changed the aspect of this subject, and have introduced two corresponding problems in excitation systems. The growing demand for increased reliability of service has required quicker response of excitation systems on the occasion of system disturbance, in order to reduce the voltage drop to a minimum. And the increase in the load per transmission circuit, and in the specific loading of synchronous machines, has brought rather sharply to the fore the limit of maximum power, which formerly was encountered only infrequently.

Quick-response excitation is of distinct advantage in important power systems where the demand for increased reliability of service is pressing; and this, of course, includes many of them. The character of the excitation system—whether of moderately rapid voltage rate, or an extremely rapid rate together with a high "ceiling" voltage—is, to a large degree, a matter of economics. It is a question to be settled by the conditions of the particular case.

But the question involves the very important aspect of increased short circuit current. The use of quick response excitation means, in general, larger switches. The general trend in this direction should be duly considered in the choice of an excitation system.

Radical increase in maximum power above the steady-state limit—*i. e.*, above the value of maximum power which has heretofore been the practical limit—has been obtained in test. This involves a state of operation which is fundamentally different in character from that of the usual present day power system. This state of operation is termed *dynamic* stability, as distinguished from the condition of steady state, or *static* stability.

The increase in maximum power has been made possible by a new and unique voltage regulator. The principle which distinguishes this regulator, designated in the paper by "type *A*", from all other existing types

is this: *for a given change in a-c. voltage, the new average exciter voltage for the new condition is reached at a continuous voltage rate equal to the actual total rate of the exciter. This is initiated promptly, and is true for all a-c. voltage changes, small as well as large.* The effect of the type *A*, or of type *B* which operates on the same principle, is to provide an equivalent negative resistance, thus giving a maximum power corresponding to constant flux linkages in the alternating field circuit. In other words, it gives a component of variable excitation voltage which is at all moments equal to the $i r$ drop, thus compensating for the resistance and therefore for the armature reaction. See Fig. 2. This made it possible to obtain in test a maximum power of 415 kw. on a system, Fig. 3, for which the steady-state limit was 110 kw. See Fig. 4. This is a much greater maximum power than obtained with any other regulator.

The effect of the type *D* regulator is equivalent to shunting the resistance of the field circuit with an inductance, thus introducing a phase displacement between the alternator field current and the excitation voltage. This is shown in Fig. 8. The maximum power is therefore less, being 190 kw., as compared with 415 kw., since the resistance cannot be completely compensated without introducing the effect of inductance. See Fig. 7.

For relatively large changes in a-c. voltage—say of the order of 10 per cent above, or 10 per cent below—the rate of the effective d-c. voltage approaches the total exciter rate with contacts closed; and for still larger changes in a-c. voltage, as in the case of a short circuit, the contacts close and stay closed, thus giving the full exciter rate. This type is thus appropriate for a normal regulator below the steady-state limit, or in the case of short circuits; but it is not so suitable for quickly regulating for small voltage changes, as required under dynamic stability.

The type *C* regulator also delays action, on account of the dashpot, until large angular oscillations are set up; and its consequent effect is equivalent to inserting an inductance shunt around the resistance, as in the case of type *D*. Hence the maximum power is also lower and the hunting is more severe than in the case of types *A* and *B*.

All other commercial types, such as the "face plate regulator" and its derivatives, and the commutator type, are still more sluggish for small voltage changes. Some of these types are efficacious for quickly changing excitation on the occasion of short circuits, but they are not appropriate for sustained operation under dynamic stability. Thus, the difference between the large increases in maximum power which have been obtained by using the new regulator, type *A*, as reported in the paper, and the increases obtained by other regulators and by hand control, is explained by the fact that the new regulator functions according to an entirely different and novel characteristic, which was chosen

with respect to the particular requirements of this problem.

Quick-response exciters are not essential to operation under dynamic stability. An increase of 100 per cent in power above the steady-state limit was obtained with the type A regulator controlling an exciter voltage rate of 24 volts/sec. on a 250 volt exciter; and an increase of 275 per cent, with a rate of 142 volts/sec. No further increase was obtained when the exciter voltage rate was further increased, even to 2300 volts/sec. Thus quick-response excitation gave no more maximum power than the low rates of ordinary exciters. But it gave as much—i. e., it did not impair the results, until the high rate of 3000 volts/sec. was reached. (Where an extremely high exciter voltage rate is used in connection with short circuits, this rate is applied only on the occasion of a short circuit. Normally it is not in the circuit.) Then instability occurred. It is thus concluded that quick-response excitation was not essential to the maximum gain in power limit obtained in the tests, because the gain was made without the use of such excitation.

But this does not mean that such an excitation system may not be desirable in a system normally operated under dynamic stability. It surely would be desirable, but for another reason—namely, to reduce the voltage drop during system disturbances, which is also the reason it is used on present systems normally operating below the steady-state limit.

It should be added that the type A and type B regulators possess the required characteristics for controlling excitation both under dynamic stability and under the condition of system disturbances such as short circuits. That is, they possess characteristics suitable for general application.

The most important aspect of the results is the possible influence on the future of power transmission. There are two phases of this which should be considered. One relates to the possible increase in the output of the synchronous machines for large central stations, or in special cases of industrial plants where momentary demands of power are greater than could be carried under steady state operation, the other, to long distance transmission.

With respect to increasing the output of synchronous machines, the foremost limitations in design formerly were heating and voltage regulation. The latter was practically removed by the advent of the automatic voltage regulator, and the former has been progressively raised, principally by improvements in ventilation, and by the reduction of energy losses—i. e., sources of heat. Consequently, the rated output has gradually approached, and has finally reached the immediate range of maximum power. Thus a new limitation is encountered. Although one cannot draw general conclusions from factory tests, yet from both the test results and theoretical considerations, there appears to be no reason at this time why the limitation of maximum power could not be set much higher by the proper

use of the new regulator, thus making possible a continued progress in higher specific loading of synchronous machines. The prospects are still more hopeful for satisfactory application in those special cases where considerable momentary overload is required from time to time. And even if normal operation were to be below the steady-state limit, less safety margin would be required, since the system would be capable of operating above the steady-state limit. That is, a new margin may thus be created by the regulator.

As to long distance transmission, the results appear very promising. With the new regulator, a maximum power equal to 90 per cent of the infinite bus value was obtained over an artificial 500 mile straightaway line. The economic limitations in the power projects involving long transmission distances have been widely discussed in the literature. The situation has been faced that the maximum power which could be transmitted over very long distances was not sufficient to justify the necessary investment. The results of the present investigation are promising with respect to the possibility of removing some of those limitations and thus placing such projects on a much more attractive basis. Future developments will show whether such hopes are justified.

There is another factor which appears to be favorable in considering the application of the regulator on large machines. In such machines the mechanical inertia is relatively greater, and the electrical transients inherently longer than in the small machines used in this investigation. Thus, it would appear that the regulator would operate under still more favorable conditions when controlling the larger machines.

ACKNOWLEDGMENTS

The author wishes to acknowledge the helpful suggestions of Messrs. C. A. Nickle and R. H. Park, and the assistance of Mr. C. C. Herskind in making the tests.

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Discussion

For discussion of this paper see page 969.

Automatic Voltage Regulators

Application to Power Transmission Systems

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WITHIN a relatively short time conditions in transmission systems, as regards continuity of service, and maximum power, have radically changed. A few years ago, the amount of power transmitted over important lines was relatively small compared with their ultimate transmitting capacity. In such cases, the systems were inherently stable, and there was a reasonable margin of power with respect to load swings and short circuits. Automatic voltage regulators were used at that time chiefly for maintaining more uniform voltage conditions than could be obtained by intermittent adjustment by hand control. Different types of regulators for this purpose have given satisfactory service for a number of years. However, conditions have gradually changed. Within the last few years the power to be transmitted has increased to such an extent that it has now become necessary to consider means seriously for increasing the maximum power and for insuring continuity of service during transient disturbances, such as load swings and short circuits. The object of this paper is to present the results of an extended investigation along these lines. A new regulator is described which will accomplish the above purposes, and the theoretical analysis is confirmed by test results.

FACTORS INFLUENCING POWER LIMITS

In order to facilitate an understanding of the principles involved and the functions of voltage regulators and exciters in a transmission system, some of the factors which determine the power limit of a system will be considered briefly. When the shaft load of a synchronous motor connected to an alternator, directly or through a transmission line, is gradually increased, a point is soon reached where no more electrical power can be supplied to the motor. The amount of power which can be thus supplied depends upon the total reactance between the generator and motor, including their internal reactances, and upon the values of excitation which exist. Small values of excitation give small values of breakdown power, and large values give large values of breakdown power.

The magnitudes of the excitation which can be applied to the machines are limited by the condition that certain predetermined terminal voltages shall not be exceeded. For different sets of fixed excitation values there will be corresponding values of terminal voltages and power when breakdown occurs. Under

these conditions of fixed field excitation, the maximum power obtained is termed the steady state or static power limit for those terminal voltages. For instance, if the power on a given system is 100,000 kw. when the machines pull apart, and if the terminal voltage is 220,000 volts at this instant, all excitations being held constant, then 100,000 kw. is the steady-state power limit for operation at 220,000 volts.

Under proper conditions of variable excitation it is possible, however, to operate beyond this limit. The first experimental evidence that this was practicable was obtained² by the use of devices which increased the excitation as a function of load current, and thus compensated for armature reaction simultaneously with its occurrence. While recognizing the advantage of such factors as mechanical inertia, damping, and electromagnetic transients in stabilizing operation during system disturbances, earlier investigation, including tests with existing standard commercial regulators, had nevertheless not brought out the full possibility of utilizing these factors in producing stable operation above the steady-state limit. Indeed they definitely showed that even if it were possible to hold the machines in synchronism significantly above that limit, this was accompanied by prohibitive hunting. Later investigation, however, showed that stable operation beyond the steady-state limit was possible with control by a vibrating contact regulator having special and unique characteristics. This will be fully discussed later.

DYNAMIC STABILITY

When operating below the steady-state power limit, machines are inherently stable, *i. e.*, with no changes in the electrical constants, certain increments of shaft power may be applied without loss of synchronism, and the machines are thus considered to be in static equilibrium. For values of transmitted power above the static power limit, conditions are radically different.

Although equilibrium may exist for certain values of excitation, power, angular displacement, etc., nevertheless, if the excitations remain constant, any increase in shaft load increases the angular displacement with a resultant decrease in transmitted power. Thus, for this condition, the rate of change of power with respect to angular displacement is negative, and any change in shaft load produces cumulative action. Fortunately, due to inertia of the moving parts, the damping action of short-circuited rotor windings, and the tendency of the flux linking the field winding to remain constant,

1. Both of General Electric Co., Schenectady, N. Y.

Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.

2. Nickle and Lawton, *An Investigation of Transmission System Power Limits*, TRANS. A. I. E. E., 1926, Vol. XLV, p. 12.

the process of falling out of step is relatively slow; and if the excitations are properly adjusted following a change in shaft power, the machines can be held in equilibrium.

Similarly, when a decrease in shaft power occurs, the angular displacement decreases with a resultant increase in transmitted power. For conditions of fixed excitation, the machines will thus continue to approach each other in phase position, and will come to equilibrium at a smaller angle for which the machines are inherently stable.

Dynamic stability may be further illustrated by

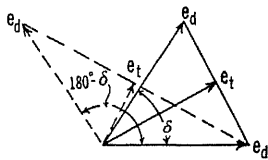


FIG. 1—VECTOR DIAGRAM FOR TWO IDENTICAL CYLINDRICAL ROTOR MACHINES ON THE SAME BUS

considering the equations of the simple case of two identical cylindrical rotor machines, connected directly together electrically.

The power as a function of the excitations or nominal voltages (assumed to be the same on both machines) and the angular displacement between the rotors, is³

$$P = \frac{e_a^2}{x} \sin \delta \quad (1)$$

where

e_a = nominal voltage corresponding to the excitations on the generator and motor.

x = total reactance of both machines.

δ = the angular displacement between the rotors.

From this relation, it may be seen that the same power may be transmitted at two values of δ , *i. e.*, one angle δ' less than 90 deg., and another angle ($180 \text{ deg.} - \delta'$) greater than 90 deg., for given values of excitation and reactance. The vector diagram is as shown in Fig. 1. From this figure, it is evident that the terminal voltage is different for these two operating angles and is given by the equation

$$e_t = e_a \cos \frac{\delta}{2} \quad (2)$$

From the standpoint of power transmitted, it is thus immaterial whether operation occurs at δ' , less than 90 deg., or at $180 \text{ deg.} - \delta'$, greater than 90 deg., for given values of nominal voltage. However, the terminal voltage will be less in the latter case, the comparison being $\cos (90 \text{ deg.} - \delta'/2)$ or $\sin \delta'/2$, with $\cos \delta'/2$. Therefore if the terminal voltage is to be the same, we must operate at greater excitations at $180 \text{ deg.} - \delta'$ than at δ' and consequently more power can be delivered.

It is considerably more difficult to maintain equilibrium at $180 \text{ deg.} - \delta'$ than at δ' since the rate of change

of power with angular displacement is negative and the machines are in a state of dynamic balance. Any increase in shaft power will cause breakdown if the excitations are not changed, and any decrease in shaft power will cause the angular displacement to revert to the inherently stable angular displacement, δ' , with a resultant abnormal rise of terminal voltage.

Operation above the static power limit thus necessitates a continually varying excitation. What appears at the present time to be the most suitable means for properly controlling these excitations is an automatic voltage regulator of suitable design.

AUTOMATIC VOLTAGE REGULATORS

Automatic voltage regulators are of two general types, *i. e.*, the rheostatic type and the vibrating contact regulator. The characteristics of different regulators of the same general type may be essentially different, depending upon the constructional features and methods of control.

Before the introduction of automatic voltage regulators, voltage was controlled by hand adjustment of rheostats in the field circuits of the exciter or alternator. Such control is necessarily rather intermittent and it is evident that a regulator designed to perform the same

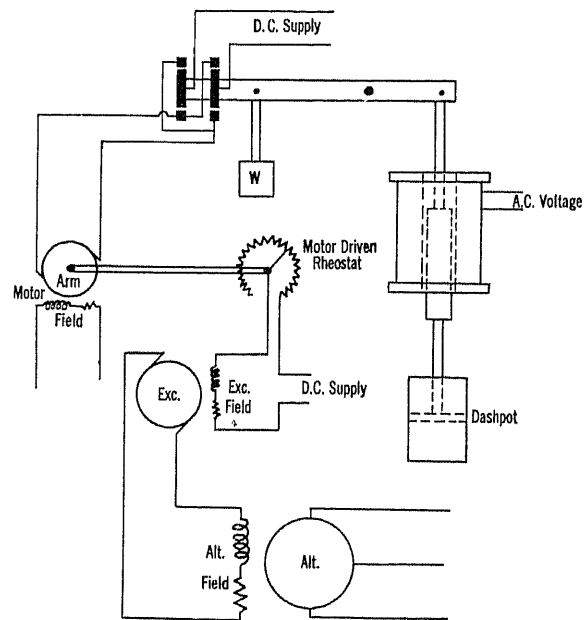


FIG. 2—SCHEMATIC DIAGRAM OF AN EXCITATION SYSTEM CONTROLLED BY A RHEOSTATIC TYPE REGULATOR

functions as hand control, but more continuously, would materially improve voltage conditions. The rheostatic type functions in this way, and for certain conditions of operation gives quite satisfactory service.

This type of automatic regulator in its simplest form consists of a motor driven rheostat, the motor being controlled by relays operated from the voltage which is to be regulated. Fig. 2 gives a schematic diagram of a

3. Doherty and Nickle, *Synchronous Machines*, TRANS. A. I. E. E., 1926, Vol. XLV, p. 927.

regulator of this type. When the voltage rises above a predetermined value, the relay connected to the regulated voltage impresses a voltage on the armature circuit of the motor, and the resistance of the motor driven rheostat is gradually increased until the regulated voltage is again normal. Similarly, when the controlled voltage decreases, the relays reverse the voltage impressed on the motor armature, thus causing the resistance of the motor driven rheostat to decrease until the regulated voltage has increased to normal value. When the regulated voltage is normal, the contacts are all open and the motor driven rheostat becomes stationary in that position which will just hold normal voltage for the particular load conditions which exist.

This regulator in its simplest form is rather sluggish in action, being merely an improvement over intermittent hand control, and is not adapted for taking care of sudden disturbances, such as short circuits, or for controlling voltage when machines are operating above the static power limit. However, this regulator may be modified in a simple manner to take effective care of short circuits occurring when machines are operating below the static power limit.

When a short circuit occurs, there is a sudden abnormal drop in terminal voltage which seriously

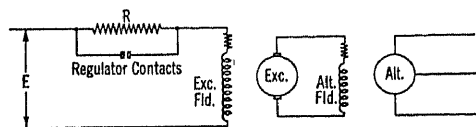


FIG. 3—SCHEMATIC DIAGRAM OF AN EXCITATION SYSTEM CONTROLLED BY VIBRATING CONTACTS

reduces the synchronizing power of the synchronous apparatus for given values of excitation, angular displacement, etc. At such times it is essential that the excitations be increased as rapidly as possible to prevent the machines breaking from synchronism. It may also be desirable to decrease the excitation rapidly when short circuits are cleared in order that the system shall not be subjected to abnormal rises of terminal voltage. These rapid changes of excitation during short-circuit conditions may be obtained by means of auxiliary relays, one of which short circuits the motor driven rheostat at such times as the resistance is being decreased, *i. e.*, immediately following a drop in terminal voltage; and another relay which inserts a normally short-circuited resistance in the exciter field circuit at such times as the resistance of the motor driven rheostat is being increased, *i. e.*, immediately following a voltage rise.

One of the advantages of such a regulator lies in the fact that, by suitable design, the entire regulator may be stationary for relatively long periods of time during steady load conditions, resulting in quietness of operation. The ratio of the time that the rheostat is in motion to the time that it is stationary is largely determined by the voltage sensitivity of the controlling

relay. The greater the sensitivity of this relay, the smaller will be the voltage change required to operate the contacts and the motor driven rheostat will be in motion a larger part of the time. With extreme sensitivity, the relays and motor driven rheostat would be in operation all the time and the regulator would be essentially a vibrating contact regulator. The sensitivity of this relay has an important effect upon the possibility of such a regulator controlling operation above the static power limit.

When machines are operating above the static power limit, they are continually in the incipient stage of breakdown. As they begin to break from synchronism, the terminal voltage changes are small, but if these small changes of terminal voltage are not corrected, the machines soon obtain sufficient velocity of separation to make it extremely difficult to restore them to equilibrium at a later instant, regardless of the speed of build-up of the excitation voltage. In order that such a regulator may respond to these small voltage changes, the controlling relay must be made very sensitive to small voltage changes with the result that the regulator will be in operation at all times, even for power transmission below the static power limit. One of the advantages of this regulator is then lost, *i. e.*, still operation over relatively long intervals of time, and it becomes essentially a vibrating contact regulator.

A characteristic common to all vibrating contact voltage regulators is that the amount of excitation is controlled by periodically short circuiting a resistance in the excitation circuit as shown in the simple diagram in Fig. 3.

When the contacts are closed all the time, maximum voltage is obtained at the exciter terminals, and when open all the time, minimum voltage is obtained. By varying the ratio of the time that the contacts are closed to the time that they are open, any value of average exciter voltage between these limits can be obtained.

There are different ways by which a vibrating contact regulator can change the average exciter voltage from one value to another. One method is to close the contacts at once and keep them closed until the desired exciter voltage is reached, vibration then being resumed at the proper ratio of time-closed to time-open to maintain this new exciter voltage.

Another way would be to change suddenly the ratio of time-closed to time-open to a value which will ultimately sustain the new value of exciter voltage. It might seem that, since the ratio of time-closed to time-open is changed suddenly to a new definite value, the new average exciter voltage is immediately obtained. This, however, is not the case, the new average exciter voltage being obtained only after a relatively long transient. The equations for this transient are derived in the Appendix.

Although, in both cases, steps are taken at once to increase the average exciter voltage, nevertheless there

is a marked difference in the time required to attain this new value. When the contacts close and remain closed until the new average exciter voltage is reached, the exciter voltage builds up at the inherent magnetic rate of the exciter, and, as a function of time, will appear as in Fig. 4. It is evident that for this case, the maximum voltage rate possible is obtained from a given excitation system.

When the ratio of time-closed to time-open is merely changed from one value to another, *normal vibration of*

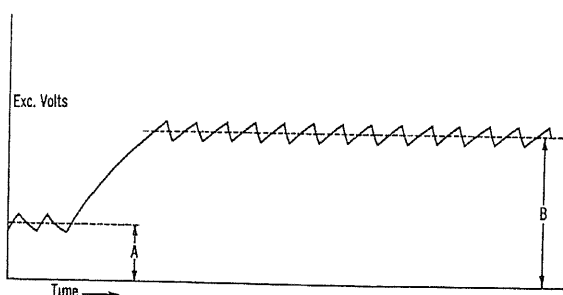


FIG. 4—VARIATION OF EXCITER VOLTAGE AS A FUNCTION OF TIME FOR THE CASE OF A SUDDEN DROP OF ALTERNATOR VOLTAGE

Contacts close and stay closed until the new value of exciter voltage is reached

the contacts is not momentarily interrupted, and the transient appears as shown in Fig. 5.

The difference in time required for a given change of exciter voltage can be readily appreciated by inspection of Figs. 4 and 5. As seen from Fig. 5, any regulator which operates on the principle of suddenly changing the ratio of the time-closed to the time-open of the contacts, causes the rate of change of average exciter voltage to

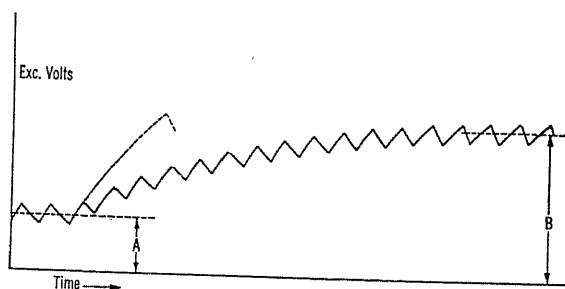


FIG. 5—VARIATION OF EXCITER VOLTAGE AS A FUNCTION OF TIME FOR THE CASE OF A SUDDEN DROP OF ALTERNATOR VOLTAGE, WHEN THE RATIO OF TIME-CLOSED TO TIME-OPEN OF THE CONTACTS SUDDENLY CHANGES

be very seriously reduced below its inherent or maximum rate, and is seriously handicapped for operation under conditions of dynamic stability. In other words, such a principle used in a scheme of voltage regulation makes the effective voltage rate of the exciter much lower than the possible rate which might be obtained.

Oscillographic verification of the curves shown in Figs. 4 and 5 are shown in Figs. 6 and 7. In making these tests to determine the effect on the exciter voltage of a sudden small reduction in the a-c. voltage, a

separate source of voltage, not controlled by the regulator, was impressed on the control coils. The relays of the regulator controlled the terminal voltage of an exciter in the usual way and the oscillograms were taken of the variation in exciter terminal voltage when the amplitude of the impressed voltage was suddenly decreased.

The difference in effective exciter voltage rate for the two cases, particularly for very small changes of impressed voltage, is so marked that a regulator operating on the first principle can effectively control machines in stable operation far above the static power

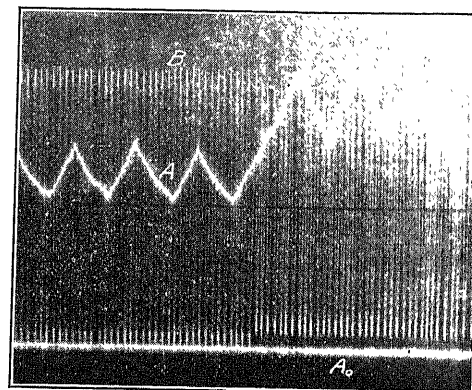


FIG. 6—OSCILLOGRAPHIC VERIFICATION OF FIG. 3, USING NEW REGULATOR

Curve A: Exciter voltage
Curve B: Alternator voltage

limit, whereas a regulator operating on the principle of suddenly changing the ratio of time-closed to time-open of the relay contacts, gives about the same results as good hand control.

Consider the simple regulator shown in Fig. 8. The

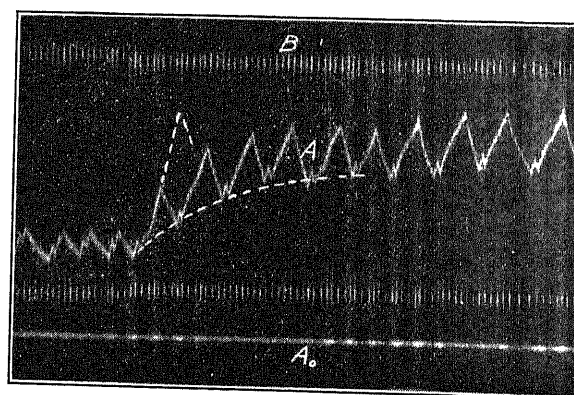


FIG. 7—OSCILLOGRAPHIC VERIFICATION OF FIG. 4, USING REGULATOR WITHOUT D-C. COIL

Curve A: Exciter voltage
Curve B: Alternator voltage

voltage which is to be regulated is impressed on coil A which is arranged to pull upward on its plunger. One end of this plunger is mechanically connected to the dashpot B and the other end is attached to the pivoted lever C. This entire lever system is adjusted by means of the weight W so that it is statically balanced when normal regulated voltage is impressed on coil A.

The lever system on the left comprises a coil *D*, connected to the armature terminals of the exciter, a plunger which is pulled downward by coil *D* and a pivoted lever *E*. The motion of this lever is opposed by the spring *F*. The contacts *G*, when closed, operate relays which short-circuit resistance in the exciter field circuit and, when open, insert this resistance. For simplicity, the contacts *G* are shown in the diagram to perform this function without the use of auxiliary relays.

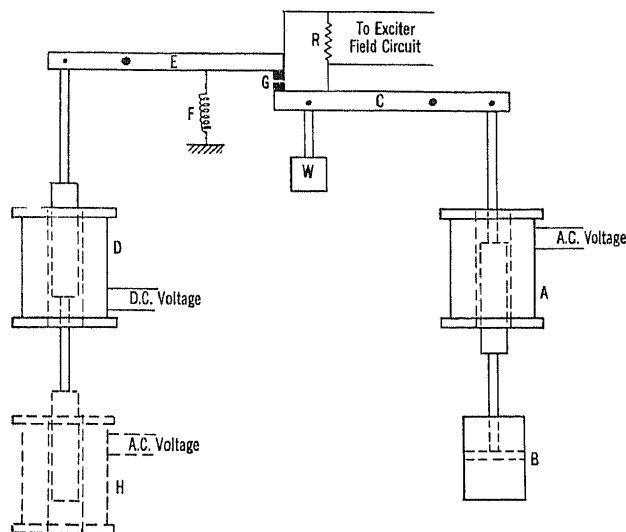


FIG. 8—SCHEMATIC DIAGRAM OF A VOLTAGE REGULATOR OF THE VIBRATING CONTACT TYPE

Assuming that the voltage impressed on coil *A* is normal, and that the lever *C* is in a given position as shown, then when the contacts are closed the resistance *R* in the exciter field circuit is short circuited and the exciter voltage increases exponentially. As it increases, the pull of coil *D* also increases and eventually becomes

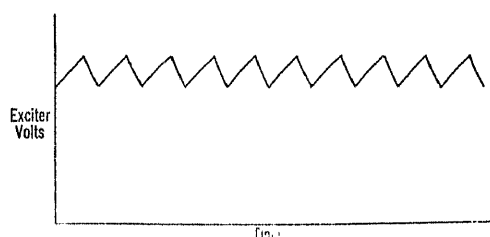


FIG. 9—VARIATION OF EXCITER VOLTAGE WITH TIME UNDER STEADY LOAD CONDITIONS

great enough to overcome the opposing pull of the spring, and the contacts open. The resistance *R* is thus inserted in the exciter field circuit, the exciter voltage decreases, the pull of coil *D* decreases and eventually, the spring overcomes the pull of coil *D* and the contacts close again. These operations then continue periodically at a frequency of the order of five cycles per sec. The exciter voltage then consists of periodic exponential increases and decreases as shown in Fig. 9. If the average value of this exciter voltage is just sufficient to maintain normal voltage on the alternator, the

regulator is in equilibrium and lever *C* remains in the assumed position. If now a drop of alternator voltage occurs, lever *C* is no longer in equilibrium and starts to rotate in a clockwise direction. As the left end gradually rises, more and more average exciter voltage is required to balance the pull of the spring. Lever *C* will thus continue to move until the exciter voltage has increased once more to a value which will just maintain normal alternator voltage. The speed of motion is controlled by the dashpot which is necessary to give stable operation. Although the dashpot is necessary to stabilize the regulator, nevertheless it introduces sluggishness of response to changes of alternator voltage. The variation of exciter voltage immediately following a sudden drop of controlled voltage then appears as shown in Fig. 10. The effective speed of exciter build-up is then largely controlled by the characteristics of the dashpot. It is interesting to note that the dashpot causes the effective speed of build-up of exciter voltage to be modified in quite a

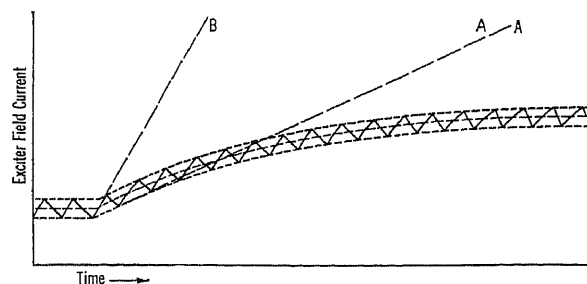


FIG. 10—CURVE SHOWING THE EFFECTIVE RATE OF CHANGE OF EXCITER FIELD CURRENT FOLLOWING A DROP OF ALTERNATOR VOLTAGE

- Slope of Line A gives the initial rate of change when the ratio of time closed to time open of the contacts suddenly changes
- Slope of Line B gives the rate of change when the contacts close and stay closed

similar manner as for a regulator which suddenly changes the ratio of time-closed to time-open following a drop in terminal voltage. The difference between the regulator described and one which suddenly changes its ratio of time-closed to time-open is thus more in degree than in principle, and neither type obtains marked increases of power above the static power limit.

When another coil *H* is added to the left hand lever system of the regulator described above, the regulated voltage being impressed on this coil, a distinct difference in operation occurs. As explained before, a definite average pull is required to overcome the force of the spring for any given position of the lever *C*. This pull is now made up of two components, one of which is a function of alternator voltage and another which is a function of exciter voltage. The exciter voltage, as before, controls the contact vibration and the total force due to both coils will appear as shown in Fig. 11. If the alternator voltage now suddenly decreases, the total pull also decreases and is no longer sufficient to overcome the counter pull of the spring and the contacts

close and remain closed until an exciter voltage is obtained which, in conjunction with the reduced alternating voltage, is again sufficient to open the contacts. The characteristic of the regulator immediately following such a disturbance is as shown in Fig. 12. *Before the contacts can start vibrating again* the exciter voltage must increase to a new definite value, the magnitude of the change depending upon the magnitude of the drop of alternating voltage. Thus,

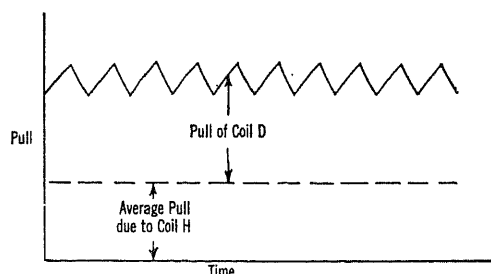


FIG. 11—MAGNETIC PULL ON LEVER *E* OF FIG. 8 AS A FUNCTION OF TIME UNDER STEADY LOAD CONDITIONS

immediately following a sudden change of alternator voltage, the exciter voltage is raised to a new level in one vibration of the contacts; and it occurs in one vibration regardless of the magnitude of the voltage drop. Hence, with an excitation system of reasonable voltage build-up rate, the average exciter voltage will vary essentially in time phase opposition to the alternator voltage variations. Furthermore, since induced field currents in the alternator are also in time phase opposition to the voltage variations, it follows that this excitation system furnishes exciter voltage changes in time phase with the alternator field current variation and thus compensates all or part of the $i r$ drop in the field circuit. In other words, the effect is obtained of introducing negative resistance in the alternator field circuit. This phenomenon is discussed in detail in a companion paper by Mr. R. E. Doherty.

The actual magnitude of the change of exciter voltage for a given change of alternating voltage may be controlled by suitable choice of the relative strengths of the coils *D* and *H*. The greater the strength of coil *H* compared with that of coil *D*, the greater will be the percentage increase of exciter voltage for a given change of alternator voltage.

It may be noted that the left hand lever system alone can never restore the regulated voltage to normal, although it can be made as nearly so as desired by controlling the relative strengths of the two coils. This is evident from the fact that if the voltage was restored to normal, the total pull required to open the contacts would be the same as its initial value, that is, the exciter voltage would be unchanged, but, by assumption, there is a drop in a-c. voltage for this exciter voltage. Hence the left hand lever alone cannot completely restore normal voltage. The final adjustment of voltage to normal is accomplished by the relatively slow movement of lever *C*.

SOME REQUIREMENTS FOR DYNAMIC STABILITY

When machines are operating under conditions of dynamic stability, they are continuously beginning to fall out of step or to approach each other in phase position with resultant voltage variations which are at first of small magnitude. Any delay of the regulator response to these voltage changes at this time has a vital effect upon the performance of the system. However, the fact that a voltage regulator closes its contacts immediately following a drop of voltage, or vice versa, is not alone sufficient to permit operation beyond the static power limit. It is extremely important that they stay closed until the exciter voltage has reached a new average level corresponding to the voltage drop which has occurred, since only in this way can the inherent voltage rate of the exciter be utilized.

When a regulator merely changes the ratio of time-closed to time-open of its contacts to a new value, the rate of build-up of average exciter voltage, *i. e.*, the effective rate, becomes smaller, the smaller the change of controlled voltage. Thus, when machines start to break from synchronism, when the voltage changes are small, the machines are permitted to gather momentum before the effective exciter voltage rate becomes great enough to be of any value. Conditions are somewhat analogous to the case of an automobile which travels 20-mi. per hr. for one hr., and attempts to travel the next 20-mi. at such a speed as to average 40-mi. per hr. for the entire distance. It cannot be done.

It is also important that the controlled exciter shall have a sufficient inherent voltage rate so that a call for increased or decreased exciter voltage by the regulator is promptly followed by the change. The impulse to change the exciter voltage, although given instantly, is of little value if the exciter cannot respond.

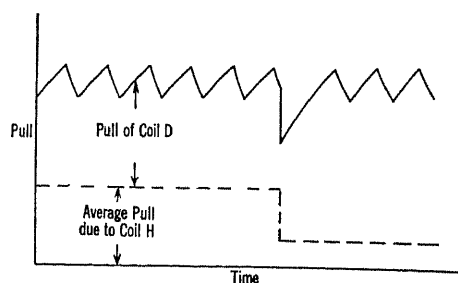


FIG. 12—MAGNETIC PULL ON LEVER *E* OF FIG. 8, AS A FUNCTION OF TIME, WHEN THE ALTERNATOR VOLTAGE SUDDENLY DECREASES

It should be noted, however, that sufficiently rapid response of exciter voltage does not necessarily require abnormal exciter voltage rates. Important gains in maximum power have been obtained with the most sluggish exciters obtainable when used in conjunction with a regulator of the proper characteristics. There are several factors, discussed later, which exert a decided influence on the requirements of exciter voltage rate for any given case.

Another requirement for dynamic stability is that the voltage regulator shall not cumulate such oscillations as might occur. Transmission systems, comprising synchronous machines, are ordinarily oscillatory, *i. e.*, when shaft loads are suddenly changed, the system does not arrive at its final position of equilibrium at once, but only after an oscillation. Once such an oscillation begins it may be either cumulated or damped out, depending upon the time phase characteristics of the regulator and excitation system. The proper time phase relations are obtained largely by the mechanical design of the regulator and the use of anti-hunting devices as have been used in the past.

The characteristics of an automatic voltage regulator and other elements of the excitation system do not alone determine the amount of power which can be transmitted over a system operating under dynamic stability. There are other important system characteristics which have a powerful influence on what a regulator and excitation system can accomplish in the way of increased maximum power.

One of these is the mechanical inertia of the rotating parts. The problem alone of operating above the static power limit would present much less difficulty if all machines had exceedingly large values of inertia. In this case, variations of shaft loads would produce such small values of acceleration that the changes in angular position, and therefore changes in terminal voltage, would be very slow—so slow that practically any kind of voltage regulation, including hand control, could maintain the voltages normal at all times and the maximum power would have the same value as for the case of infinite busses.

This may be illustrated by considering the analogous case of balancing on one's hand, a rod with a weight on the upper end. As the distance of the weight from the point of support is increased, the torque, for a given angular displacement from the vertical, is increased in direct proportion, but the moment of inertia is increased as the square of the distance. Hence, for any angular displacement, the angular acceleration is inversely proportional to the distance, and the necessity for very rapid response of the hand decreases. It is this difference which makes it so much more difficult to balance a toothpick than a ten-ft. rod.

Now in the case of synchronous machines, with finite values of inertia it is more difficult to maintain dynamic equilibrium; and with no inertia at all, it would be extremely difficult with practical regulators and excitation systems if other factors were not present.

One of the most important of these is damping. When machines drift apart in phase position, the terminal voltage also shifts and there is relative motion between the rotating fluxes in the machines and the rotor windings. This relative movement causes currents to be induced in the short circuited rotor windings and a torque arises which has a component proportional to this relative velocity at a given instant. Such a torque

constitutes damping and causes the drift out of synchronism to occur more sluggishly than if it were not present. Increased damping action thus permits more time for the excitation system to function, and dynamic stability is thus more readily maintained.

Still another important factor exists, namely, the electromagnetic inertia of the field windings. As machines change their relative phase position, the armature current changes and tends to increase or decrease the flux linking the main field winding, depending on the nature of the current change. This change in flux linking the field winding is not instantaneous, but occurs exponentially with time, its rate of change depending on the constants of the field circuit. Thus, due to the electromagnetic inertia of the field circuit, the inherent tendency is for the field current to change spontaneously in the right direction to increase stability.

Considering the limiting case of zero resistance, the flux linking the field circuit could never change without changing the impressed voltage, and any regulator could obtain a maximum power corresponding to conditions of constant flux linking the field winding instead of constant current, *i. e.*, transient reactance would be effective for conditions where synchronous reactance is now effective.

An approach toward conditions of constant flux linkages in the field circuit can be made in different ways. Either a decrease of resistance or an increase of inductance will tend toward constant flux linkages. When this result is obtained by reducing the resistance, the transient reactance is unchanged and an increased time constant is obtained without harmful results. However, if inductance were inserted in the field circuit, the increase in transient reactance more than offsets the benefits gained by the increased time constant. For infinite inductance in the field circuit, synchronous reactance is effective at all times, since conditions of constant field current would then exist. The maximum power would then be the static power limit, by definition.

Any one of these factors, described above, may make it possible to operate machines above their static power limit. It so occurs, however, that even with all three available, the full advantage of their combined effect cannot be utilized in increasing the maximum power unless a more effective control of the excitation is available than has been in the past. In order to use these factors to the greatest advantage, a new regulator, with the features already described, has been designed. With this regulator, decisive increases in maximum power have been obtained in test. These are also given in a companion paper by Mr. R. E. Doherty.

EFFECT OF CONSTANTS OF THE FIELD CIRCUIT

It has been pointed out that damping and electromagnetic inertia make operation under conditions of dynamic stability more easily obtained. When the

resistance of the field circuit is increased, the damping torque for given values of slip, and the time constant of the field circuit, are both decreased. It would then be expected that, for a given excitation system, the maximum power would be decreased when resistance is inserted in the field circuit.

The insertion of external inductance in the field circuit, *i. e.*, increasing the leakage and transient reactances, also influences maximum power. Although field inductance increases the tendency toward constant flux linkages in the field circuit by increasing the time constant, nevertheless it also increases transient reactance which more than offsets the benefits of the increased time constant. For infinite reactance, constant field current would exist and, as already mentioned, the dynamic power limit would be identical with the static power limit.

These effects of resistance and inductance in the field circuit on maximum power have been verified by tests and the results are shown in Fig. 13.

Although it is true that the effect of increased field

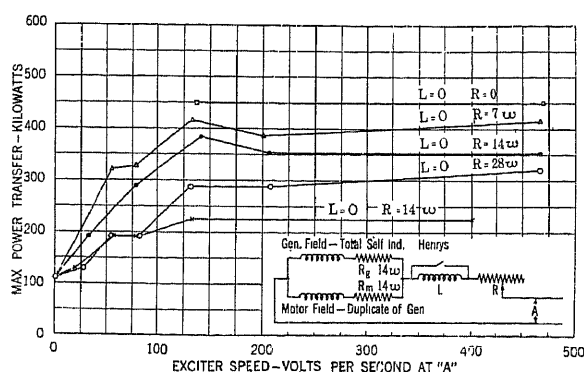


FIG. 13—RELATION BETWEEN MAXIMUM POWER AND EXCITER VOLTAGE RATE FOR DIFFERENT VALUES OF RESISTANCE AND INDUCTANCE IN THE ALTERNATOR FIELD CIRCUITS

Circuit connections as shown in Fig. 16

resistance may be counteracted by changing the regulator characteristic⁴, nevertheless, it introduces more difficulties in regulator design. Furthermore, inherently low resistance, as far as it is economically obtainable, is to be preferred to artificial low resistance.

SHORT CIRCUITS

Sudden disturbances, such as short circuits, result in a sudden drop in terminal voltage with a resultant loss of considerable synchronizing power for given conditions of angular displacement, fluxes, field currents, etc. Hence, at the instant a short circuit occurs, the angular displacement between the various machines begins to change and sufficient momentum may soon be acquired to cause loss of synchronism if corrective measures are not taken at once and as rapidly as possible.

4. As has been pointed out, a new regulator is available which has the effective characteristic of introducing negative resistance in the field circuit, the value of this negative resistance depending on the regulator constants.

Just as in the case of dynamic stability, inherent damping, inertia, and the tendency toward constant air-gap flux are favorable, their general effect being to increase the time required for breakdown to occur after a short circuit and in some cases they may, acting alone, prevent breakdown from occurring at all, if the short circuit is cleared in a reasonable time. In general, more time is permitted for excitation changes when these factors are large than when they are small.

However, such favorable factors as do exist do not seem to be sufficiently effective to allow the use of exciter voltage rates available in standard excitation systems, although these rates are sufficient for dynamic stability. This point is fully discussed in the companion paper by Mr. R. E. Doherty. As pointed out in that paper, the requirements of an excitation system to take care of short circuits are that the change of exciter voltage be initiated at once, and that it increase at a very rapid rate to the value which has been determined by the conditions of the particular case.

To fulfil the above requirements, the regulator must promptly close its contacts and keep them closed until the proper excitation voltage is reached, and the exciter voltage rate must be relatively high. Moreover, the regulator must not distinguish between phases—*i. e.*, it must act the same way regardless of the phase on which the short circuit occurs. Regulators which will accomplish this are commercially available.

If the a-c. voltage change is non-symmetrical, *i. e.*, different on the different phases, as in the case of single-phase short circuits, the response of a regulator controlled from one phase only will be different, depending upon the phase to which it is connected. In order that the regulator action shall be the same, regardless of the phase which is short circuited, various schemes are available. One of them provides an actuating a-c. voltage for the regulator which is proportional to the positive phase sequence component of the 3-phase line voltage. Another scheme, which is very effective, is to replace the usual a-c. voltage coil of the regulator in Fig. 8 by a small polyphase stationary torque motor, the shaft of which replaces the pivot of the right hand lever. A dead short circuit on any phase then causes the torque of this motor to become zero, and therefore maximum effectiveness in increasing the exciter voltage is obtained.

TEST RESULTS

During the last few years, much valuable information has been obtained and many questions have been answered by extensive factory tests, and also field tests. The latter will appear in a forthcoming paper. The first tests, in which the new regulator was used, were made on small 3.75 kw. machines with an interconnecting transmission line. The motor and generator were identical, each having a direct synchronous reactance 1.55 and a quadrature reactance 0.30 on the basis of 10 kv-a. at 100 volts, line to line. On this same basis,

the reactance of the interconnecting line was 1.0 and the resistance was 0.05. The diagram of connections for this system is shown in Fig. 14. A shunt motor drove a synchronous generator which delivered power over a transmission line to a synchronous motor. This motor drove a shunt generator which could be loaded by means of a resistance across its terminals. The excitation was furnished by a 3-kw., 1800-rev. per min., 125-volt shunt wound exciter. During these tests

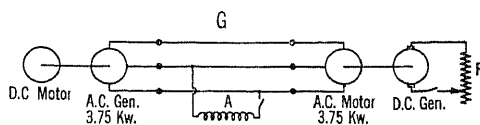


FIG. 14—SCHEMATIC DIAGRAM OF THE SMALL TRANSMISSION SYSTEM USED IN THE TESTS

self excitation and separate excitation with different voltages impressed on the field circuit of the exciter were used. In this way, exciter voltage rates ranging from 50 to 400 volts per sec. could be obtained.

The first tests on this system were to determine the static power limit. For various values of fixed excitation on the motor and generator, power-voltage curves were taken and the results are shown in Fig. 15. From the locus of maximum power points, the static power limit for any operating voltage may be determined. The operating voltage used throughout these tests was

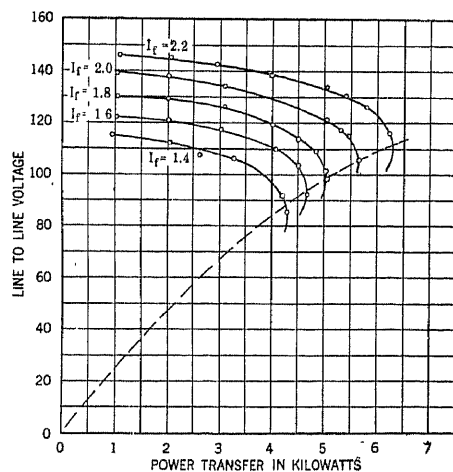


FIG. 15—POWER-VOLTAGE CURVES BY CALCULATION AND TEST

Two AHI-4-3.75-1800-110-volt synchronous machines connected through a transmission line. Excitation on motor and generator held constant at different values

110 volts, giving a static power limit of 6.1 kw. The maximum power of the line alone, *i. e.*, with infinite busses at each end, is neglecting resistance 12.0 kw.

Tests were then made to determine the effect of exciter voltage rate on maximum power when commercial regulators, including both the types with d-c. coil and without d-c. coil, were used. The results showed that the maximum power was practically independent of exciter voltage rate for these regulators, the same

power, *i. e.*, 7 kw., being obtained with various commercial regulators for widely different values of exciter voltage rate. It is interesting to note that this same value of power, slightly above the static power limit was also obtained by hand control. However, when the new regulator was used, the difference became apparent at once. The maximum power was increased immediately to 10 kw. and after careful adjustment this was increased to 11 kw., or a gain of approximately 60 per cent. When it is considered that the possible gain, assuming infinite busses at each end, is 70 per cent, the results are seen to contain elements of great practical importance.

The system was also shown to be remarkably stable to sudden shocks. A reactor, A, whose reactance was of such a value as to take a current of the order of normal current on the basis of 10 kv-a. at 100 volts, could be repeatedly connected across the terminals, and disconnected, and the system remained in synchronism, even when carrying a load of 9 kw. or 30 per cent more

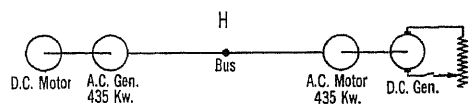


FIG. 16—DIAGRAM FOR LARGER TRANSMISSION SYSTEM USED IN TESTS

Machine Ratings:

Alternator and Motor: TS-435-1200-4000/2300 volts

D-c. Motor and Generator: MPC-6-300-1200-250/275 volts

Exciter: MP-4-17-700-250 volts—68 amperes

than standard regulators could obtain under steady conditions.

Question then arose concerning the difference that might be obtained using a larger system. Therefore another system, shown in Fig. 16, was set up, using machines having a rating of 435 kv-a. at normal voltage, *i. e.*, at 4000 volts. The synchronous reactance on this basis was 1.18 and the quadrature reactance was 0.62. For excitation purposes, a separately excited, 4-pole, 20 kw., 1200-rev. per min., 125-volt exciter was used in conjunction with various types of voltage regulators. During these tests, the machines were operated at reduced voltage, *i. e.*, 2200 volts, in order that the d-c. machines should not be too heavily overloaded. At this reduced voltage, the static power limit, as determined by power voltage curves taken under conditions of constant excitation, was 120 kw. With standard commercial regulators and with hand control, a maximum power of 180 kw. was obtained, this power being practically independent of the exciter voltage rate. The new regulator increased this power to 480 kw., approximately an increase of 170 per cent, *i. e.*, the maximum power was almost tripled.

Tests were also made on this system under short-circuit conditions. The short circuit comprised a resistance of 47 ohms, or 1.28 on the basis of 435 kv-a. at 4000 volts. This partial short circuit was left on

for 0.8 sec. and under these severe conditions, the machines remained in synchronism when carrying an initial load of 330 kw. which is almost twice as much as could be carried by the system with standard regulators under steady conditions.

At a later date a similar system was set up, using machines of the same rating but having a slightly higher value of synchronous impedance, *i. e.*, 1.27 on the basis of 435 kv-a. at 4000 volts. These machines, as in

the results of the tests are shown in Fig. 18. It may be noted that large gains in maximum power are obtained with this new regulator, using exciter voltage rates readily obtainable in standard exciters.

The effects of resistance and inductance inserted in the field circuit were also determined. As previously pointed out, increasing these constants should make it more difficult to obtain large gains in maximum power. These conclusions are justified by the results shown in Fig. 13.

Appendix

THEORETICAL CONSIDERATIONS OF VIBRATING CONTACTS

It has been explained that a vibrating contact voltage regulator controls the average exciter voltage by maintaining different ratios of the time that the contacts are closed across a resistance in the exciter field circuit to the time that they are open. Two methods are available for changing from one exciter voltage to another. The contacts may be closed and kept closed until the new average voltage is obtained, vibration being then resumed at a new ratio of time-close to time-open which will maintain the new exciter voltage;

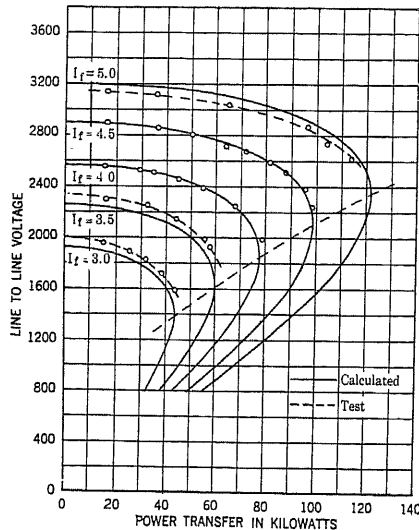


FIG. 17—POWER-VOLTAGE CURVES BY CALCULATION AND TEST

Two TS-6-435-1200-4000/2300-volt synchronous machines connected to the same bus. Excitation on motor and generator held constant at different values

previous tests, were operated at reduced voltage, in this case, 2240 volts, and the power voltage curves under conditions of constant excitation are given in Fig. 17.

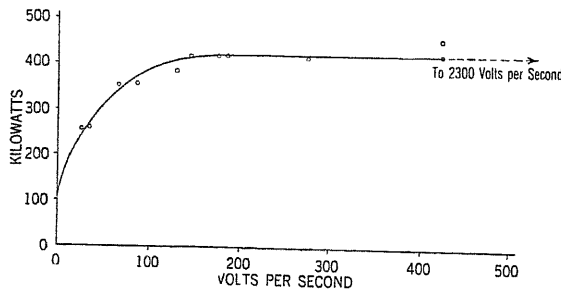


FIG. 18—MAXIMUM POWER AS A FUNCTION OF THE EXCITER VOLTAGE BUILD-UP RATE FOR THE TEST SET-UP OF FIG. 16, USING NEW REGULATOR

The static power limit at 2240 volts is thus 110 kw. When standard automatic voltage regulators were used, as well as hand control, the maximum power under steady load conditions was of the order of 200 kw. The new regulator with the same excitation system increased the maximum power to 415 kw.

Previous tests had indicated that extremely high exciter voltage rates were unnecessary for increasing the maximum power under steady load conditions. Tests were made on this new system to verify this and

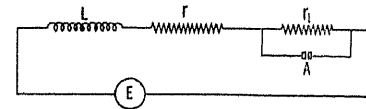


FIG. 19—ELECTRIC CIRCUIT IN WHICH THE AVERAGE CURRENT IS CONTROLLED BY VIBRATING CONTACTS

or, the ratio of time-closed to time-open may be suddenly changed to its new value, vibration of the contacts being continuously maintained.

The transient during the change from one exciter voltage to another is entirely different for the two methods as will be seen from the following analysis.

Consider the circuit shown in Fig. 19 and let

L = inductance of the circuit in henrys.

r = resistance permanently in the circuit.

r_1 = resistance periodically short circuited by the contacts, A .

E = the constant impressed voltage.

$$r_2 = r + r_1$$

When the contacts are closed, the differential equation for the circuit is

$$L \frac{di}{dt} + r i = E \quad (1)$$

The solution of equation (1) is

$$i = \frac{E}{r} - \left(\frac{E}{r} - i_1 \right) e^{-\alpha(t-t_1)} \quad (2)$$

where i_1 = the current at the instant the contacts close.

$$\alpha = \frac{r}{L}$$

t_1 = time at which the contacts close.

When the contacts are open the differential equation is

$$L \frac{di}{dt} + r_2 i = E \quad (3)$$

and the solution is

$$i = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_2 \right) e^{-\beta(t-t_2)} \quad (4)$$

where i_2 = the current at the instant the contacts open.

$$\beta = \frac{r_2}{L}$$

t_2 = the time at which the contacts open.

When the contacts are operating under sustained conditions, the final current of equation (2), *i. e.*, at $t = t_2$, must equal the initial current of equation (4), and also the final current of equation (4), *i. e.*, at $t = t_3$, must equal the initial current of equation (2).

$$\text{Hence } i_{2s} = \frac{E}{r} - \left(\frac{E}{r} - i_{1s} \right) e^{-\alpha(t_2-t_1)} \quad (5)$$

$$i_{1s} = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_{2s} \right) e^{-\beta(t_3-t_2)} \quad (6)$$

where

i_{2s} = the final current with the contacts closed and the initial current with the contacts open, under sustained conditions.

i_{1s} = the initial current with the contacts closed and the final currents with the contacts open.

Evidently, $t_2 - t_1$ is the time during which the contacts are closed in each vibration and $t_3 - t_2$ is the time that they are open. Letting

$$t_2 - t_1 = t_c = \text{time closed} \quad (7)$$

$$t_3 - t_2 = t_o = \text{time open} \quad (8)$$

equations (5) and (6) become

$$i_{2s} = \frac{E}{r} - \left(\frac{E}{r} - i_{1s} \right) e^{-\alpha t_c} \quad (9)$$

$$i_{1s} = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_{2s} \right) e^{-\beta t_o} \quad (10)$$

Solving these simultaneous equations for i_{2s} and i_{1s}

$$i_{1s} = E \left\{ \frac{\frac{1}{r_2} - \frac{1}{r_2} e^{-\beta t_o} + \frac{1}{r} e^{-\beta t_o} - \frac{1}{r} e^{-(\alpha t_c + \beta t_o)}}{1 - e^{-(\alpha t_c + \beta t_o)}} \right\} \quad (11)$$

$$i_{2s} = E \left\{ \frac{\frac{1}{r} - \frac{1}{r} e^{-\alpha t_c} + \frac{1}{r_2} e^{-\alpha t_c} - \frac{1}{r_2} e^{-(\alpha t_c + \beta t_o)}}{1 - e^{-(\alpha t_c + \beta t_o)}} \right\} \quad (12)$$

Equations (11) and (12) determine the minimum value, i_{1s} , and the maximum value, i_{2s} , of the exciter

field current under sustained conditions. The variation of current between these limits is given by equations (2) and (4). The current in the circuit, under sustained conditions, then has the form shown in Fig. 20.

The average current under sustained conditions is obtained as follows:

The area under the current curve during one inter-

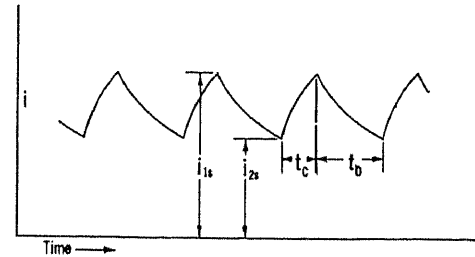


FIG. 20—CURRENT IN THE CIRCUIT OF FIG. 19 AS A FUNCTION OF TIME

val when the contacts are closed is, from equation (2),

$$A_c = \int_{t=t_1}^{t=t_2} \left\{ \frac{E}{r} - \left(\frac{E}{r} - i_1 \right) e^{-\alpha(t-t_1)} \right\} dt \quad (13)$$

$$= \frac{E}{r} t_c - \frac{E}{r \alpha} + \frac{E}{r \alpha} e^{-\alpha t_c} + \frac{i_1}{\alpha} (1 - e^{-\alpha t_c}) \quad (14)$$

The area of the current curve during one interval when the contacts are open is, from equation (4),

$$A_o = \int_{t=t_2}^{t=t_3} \left\{ \frac{E}{r_2} - \left(\frac{E}{r_2} - i_2 \right) e^{-\beta(t-t_2)} \right\} dt \quad (15)$$

$$= \frac{E}{r_2} t_o - \frac{E}{r_2 \beta} + \frac{E}{r_2 \beta} e^{-\beta t_o} + \frac{i_2}{\beta} (1 - e^{-\beta t_o}) \quad (16)$$

The average current is then the sum of (14) and (16) divided by one period of the contacts, $t_o + t_c$, or

$$i_{ave} = \frac{E \left\{ \frac{t_c}{r} + \frac{t_o}{r_2} - \frac{1}{r \alpha} - \frac{1}{r_2 \beta} + \frac{1}{r \alpha} e^{-\alpha t_c} + \frac{1}{r_2 \beta} e^{-\beta t_o} \right\} + \frac{i_1}{\alpha} (1 - e^{-\alpha t_c}) + \frac{i_2}{\beta} (1 - e^{-\beta t_o})}{t_o + t_c} \quad (17)$$

When equations (11) and (12) are substituted in (17) the average sustained current is,

$$i_{ave} = E \left\{ \frac{\frac{t_c}{r} + \frac{t_o}{r_2}}{t_o + t_c} - \frac{L}{t_o + t_c} \left(\frac{r_2 - r}{r_2 r} \right)^2 \right\}$$

$$\left\{ \frac{(1 - e^{-\beta t_0})(1 - e^{-\alpha t_c})}{(1 - e^{-(\alpha t_c + \beta t_0)})} \right\} \quad (18)$$

Since $\frac{1}{r}$ is the conductance of the circuit when the contacts are closed, and $\frac{1}{r_2}$ is the conductance when the contacts are open, the average current, when $L = 0$, is

$$i_{ave} = E \text{ (average conductance)} \quad (19)$$

$$L = 0$$

When L is very large or when the frequency of vibration of the contacts is very large, equation (18) approaches the value

$$i_{ave} = \frac{E}{\frac{r t_c + r_2 t_0}{t_0 + t_c}} \quad (20)$$

$$L = \infty \text{ or } t_0 + t_c = 0$$

or the average current, for these conditions, is determined by the average resistance. In most practical cases, the combined effects of inductance and contact frequency will be sufficiently great to make equation (20) a good working approximation.

The manner in which the average sustained current changes from one average value to another is of importance in the problem of maximum power. When the change is initiated by suddenly changing the ratio of the time that the contacts are closed to the time that they are open, the new sustained value of current is not attained in one vibration of the contacts but only after a relatively long transient. For one closing of the contacts at the time t_1 , the initial current is i_1 . The current increases to i_2 determined by equation (2), and i_2 is the initial current when the contacts open. After they open, the current decreases to a new value

$$i_3 = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_2 \right) e^{-\beta t_0} \quad (21)$$

determined by equation (4), and i_3 is the initial current when the contacts again close. Under sustained conditions, $i_3 = i_1$, but when the ratio of t_c to t_0 is suddenly changed, $i_3 \neq i_1$ until the new sustained values are reached.

During the transient period, the difference between i_1 , for a given closing of the contacts, and its final sustained value, i_s , given by equation (11), is

$$i_{1s} - i_1 = E \left\{ \frac{\frac{1}{r_2} - \frac{1}{r_2} e^{-\beta t_0} + \frac{1}{r} e^{-\beta t_0} - \frac{1}{r} e^{-(\alpha t_c + \beta t_0)}}{(1 - e^{-(\alpha t_c + \beta t_0)})} \right\} - i_1 \quad (22)$$

The difference between the new sustained value, i_{1s} , and i_3 , one cycle of vibration later, is

$$i_{1s} - i_3 = E e^{-(\alpha t_c + \beta t_0)} \left\{ \frac{\frac{1}{r_2} - \frac{1}{r_2} e^{-\beta t_0} + \frac{1}{r} e^{-\beta t_0} - \frac{1}{r} e^{-(\alpha t_c + \beta t_0)}}{(1 - e^{-(\alpha t_c + \beta t_0)})} \right\} - i_1 e^{-(\alpha t_c + \beta t_0)} \quad (23)$$

The ratio obtained by dividing (23) by (22) is

$$d = e^{-(\alpha t_c + \beta t_0)} \quad (24)$$

This is the value of the decrement of the minimum current values per cycle of vibration of the contacts. Since this ratio is constant, the envelope of the minimum current values is exponential in form, and the current, for any instant at which the contacts close, is

$$i_1 = i_{1s} - (i_{1s} - i_{10}) e^{-\left(\frac{\alpha t_c + \beta t_0}{t_c + t_0}\right) t} \quad (25)$$

The decrement factor of (25) is

$$\sigma = \frac{\alpha t_c + \beta t_0}{t_c + t_0} = \frac{r t_c + r_2 t_0}{L(t_c + t_0)} = \frac{\text{average resistance}}{L} \quad (26)$$

It is interesting to note that although the sustained average current is determined by the average conductance when L is zero, [equation (19)], by the average resistance when $L = \infty$, [equation (20)] and by some intermediate value when the inductance is finite, nevertheless, the time constant during a transition period is always a function of average resistance.

It can be shown that the maximum current peaks and average current also vary according to the same exponential law. Hence, when the ratio of time-closed to time-open is suddenly changed, the average current changes from its initial sustained value to its final sustained value according to equation (27).

$$i_{ave} = i_s - (i_s - i_0) e^{-\frac{\text{average resistance}}{L} t} \quad (27)$$

where i_s is the final and i_0 the initial sustained average current. During this transient, the current will appear as shown in Fig. 10.

Inspection of Fig. 10 shows how much slower the exciter field current builds up when the contacts open and close during the change in field current than when they close and remain closed until the exciter field current has reached its new value. With the slower scheme, the effective rate of change of exciter field current is given by the slope of the exponential curve through the current peaks, i. e., by the slope of line A; whereas, if the contacts close and stay closed until the new average value of exciter field current is reached, the effective rate of change of field current is given by the slope of line B. The new regulator functions in this way and the marked results obtained with it are largely due to this characteristic.

The superiority of this principle may be brought out by the following example.

Let Fig. (21) represent the saturation curve and field characteristic of an exciter which is controlled by a regulator whose contacts close and open during the

change in field current. Assume that the contacts are vibrating 5-times per sec. and that the initial time-closed and time-open intervals are

$$t_c = 0.04 \text{ sec.}$$

$$t_o = 0.16 \text{ sec.}$$

Then the average field current, determined by equation (21), is 3.67 amperes, the corresponding exciter

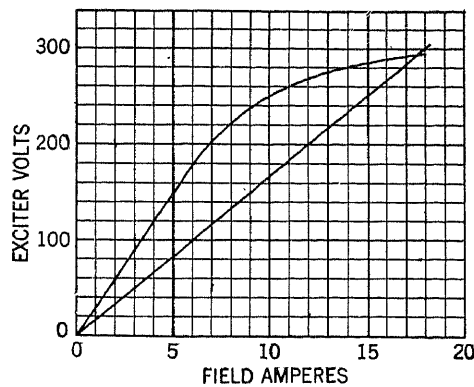


FIG. 21—SATURATION CURVE AND FIELD CHARACTERISTIC OF THE EXCITER USED IN THE NUMERICAL EXAMPLE

Voltage impressed on exciter field, 500 volts. Resistance of field winding, 16.67 ohms. External resistance, 166.67 ohms

voltage, from Fig. 21 is 110 volts, and the ratio of time-

closed to time-open is $\frac{t_c}{t_o} = 0.25$.

When the ratio of time-closed to time-open is suddenly increased to some new value, the initial rate of change of average exciter field current, can be determined by means of equations (18) and (27). The rate of change of average exciter voltage may then be obtained from Fig. 21. The curve in Fig. 22 shows the

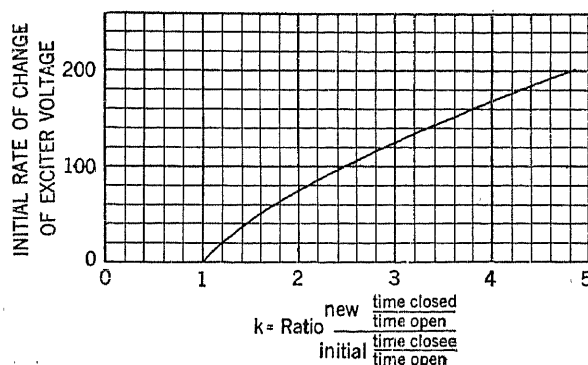


FIG. 22—RATE OF CHANGE OF AVERAGE EXCITER VOLTAGE AS A FUNCTION OF CHANGES OF THE RATIO OF TIME-CLOSED TO TIME-OPEN OF THE VIBRATING CONTACTS

initial rate of change of average exciter voltage in volts per second when the ratio of time-closed to time-open is changed.

It will be noticed that, as the change in this ratio becomes smaller, the effective rate of change of exciter voltage also becomes smaller, approaching zero as a limit. Hence at incipient breakdown, where the

changes of this ratio are small, a regulator which closes and opens its contacts during the change in field current is very ineffective and the synchronous machines will acquire some momentum on their way out of synchronism before the regulator becomes very effective. It is thus apparent that the machines are allowed to get under way, out of synchronism which is usually fatal as far as operation under conditions of dynamic stability is concerned.

If, with the same exciter, a regulator is used which keeps its contacts closed during the transient, the initial rate of change of average exciter voltage becomes 438 volts per sec.

Therefore, a regulator which continues to vibrate its contacts during a change of exciter field current causes the apparent or effective speed of exciter build-up to be markedly less than its inherent speed.

In many cases, the necessity for abnormal exciter voltage rates may be overcome by using the new regulator which takes advantage of the inherent exciter speed at all times.

Discussion

C. A. Powell: The problem of quick-response excitation in its relation to stability is one of great importance, and one in which I have been much interested. In fact, I believe my paper prepared for the "High Voltage Conference" at Paris last year, and later published in the *Electric Journal* of April 1927, was the first one devoted exclusively to quick-response excitation. Mr. Doherty's paper is interesting and valuable in itself, and also because it disposes of a controversy over a major question in the general problem of stability. He refers to a heretofore unexploited zone of artificial stability, and it may be interesting to review the work previously done in this zone.

At the A. I. E. E. Mid-Winter Convention in 1924, E. B. Shand¹ suggested that operation in the zone of artificial stability might be possible if we could change the excitation within the synchronous machine quickly enough. The idea was further developed in the course of our work on high voltage transmission, and at the Mid-Winter Convention in 1925, Messrs. Fortescue and Wagner² were able to amplify considerably Mr. Shand's ideas. In September 1925, at the Seattle Convention, Mr. Fortescue³ definitely proposed an increased speed of excitation obtained by regulator control as a means of increasing the stability of a transmission system, and Mr. Doherty and his colleagues specifically disagreed with him, maintaining the position that quick response, if it was to be obtained by means of a voltage regulator, would not make it possible to carry a constant load significantly greater than with hand control. Mr. Doherty expressed himself as being of the opinion that improvements by compensation rather than by regulation were a more hopeful field for future development. Such improvements have been suggested in the past and involve either a series exciter or compounding by means of rectifiers or converters.

At the Mid-Winter Convention in 1926, Messrs. Evans and Wagner⁴ presented a paper which summarized the exploitation, by them and their colleagues, of the range of operation of syn-

1. *The Limitations of Output of a Power System Involving Long Transmission Lines*. A. I. E. E. TRANS., 1924, Vol. XLIII, p. 59.
2. A. I. E. E. TRANS., 1925, Vol. XLIV, pp. 98-101.
3. *Transmission Stability*, C. L. Fortescue, A. I. E. E. TRANS., 1925, Vol. XLIV, p. 984.
4. *Studies of Transmission Stability*, A. I. E. E. TRANS., 1926, Vol. XLV, p. 51.

chronous machines beyond the static limit as set by constant excitation, both with steady loads and under transient conditions. At the time, Mr. Doherty and Mr. Nickle again asserted that the only function of the regulator was to increase automatically the excitation as the load is applied, the actual load limit being the same as for hand control; whereas Messrs. Evans and Wagner described in their closing discussion tests made at Pittsburgh in 1925. The tests were made with an artificial line having 100 per cent reactance based on the normal rating of the machines, and using a standard Westinghouse vibrating regulator. With this combination, a substantial increase over the static limit was transmitted over this miniature system.

In one of the subsequent tests described by Mr. Doherty in the paper under discussion, he obtained four times the static limit of the system with a set-up consisting of a generator and motor on a common bus with a common exciter and regulator. Now with ideal excitation and neglecting losses and saturation, the theoretical power limit of such a set-up would be infinity; whereas with a set-up consisting of a generator and motor connected by a transmission line, the stability limit is the power limit of the line itself, which is finite. The tests which Mr. Doherty reports, using an artificial line and independent control of the sending and receiving machines, give results higher than the tests made in Pittsburgh in 1925, but the latter were made with a view of establishing the facts, and not of finding the ultimate limit.

The tests are interesting, but I question if they are of the practical value that the paper implies. The true power limit of a system under present-day conditions is defined by its stability under transient conditions. Those who are operating transmission systems know that when the two ends of a system pull apart, they do so at times of a disturbance, and not as a result of slowly added load. Now for transient conditions, any a-c. control regulator, such as the Westinghouse regulator, that closes its contacts promptly and keeps them closed until the a-c. voltage is back to approximately normal, is suitable. After the regulator has closed its contacts, the recovery of the a-c. voltage is a function of the response of the exciter and generator.

Moreover, operating a system with steady loads in the zone of artificial stability as suggested, requires that the rotors of the generating units be worked at very high values of excitation, and it may be more desirable, either to increase the static limit itself by reducing the reactance of the generators, or to supply the excitation at more appropriate locations along the transmission system, as advocated in the Baum system of transmission using intermediate synchronous condensers.

R. D. Evans: Concerning the relation of excitation to stability, there are, as Mr. Doherty points out, two distinct problems involved:

1. The use of excitation systems to increase transient limits of power systems.
2. The use of excitation systems to increase the steady load limits of power systems.

The question naturally arises as to the relative importance of these two uses of excitation systems. This depends, of course, on whether the static limit or the transient limit is the criterion for establishing the permissible loading of the power system. The oscillographic records of operating experiences on the Southern California Edison Company system, given in the paper by Messrs. Wood, Hunt, and Griscom, presented at the Pacific Coast Convention of the A. I. E. E. last September, have established that the transient limit is the more important. Ignoring those cases involving low excitation due to line-charging condition, very small ties, insufficient frequency-changer ties, and so on, there is only one case on record where the static limit of a large power transmission system has been exceeded and that case occurred under very abnormal operating conditions. Thus one must conclude that the use of excitation systems to increase

transient stability limits is the immediate problem while the increase in static limit is of less pressing nature.

Now I wish to stress the fact that considerations of transient limits have been controlling in the acceptance and adoption of quick-response excitation. Quick response was not made possible by the introduction of any new regulator, as its advantages can be obtained with existing forms of a-c. regulators. The recognition of the interest in this method of increasing the transient limit is evidenced by the fact that while the first order for such apparatus was placed during 1926, the scheme has been so widely adopted that the Westinghouse Company alone has received orders for quick-response excitation systems for about one million kv-a. of synchronous machines.

As to the requirements of excitation systems for increasing the transient limits, the most important are:

For the voltage regulator:

1. It shall close the contacts promptly upon a demand for increased excitation.
2. It shall keep the contacts closed until the a-c. voltage is restored to an appropriate value.
3. It shall possess the necessary anti-hunting features.

For the exciter:

It shall possess quick response.

Mr. Doherty attempts to define quick-response systems in terms of exciter characteristics, that is, in terms of volts per second. Such a definition, however, is not fundamental to quick response to increase stability limits of power systems. Any excitation system (which, of course, includes the regulator as well as the exciter) which is sufficiently quick to make an important change in the excitation voltage before the synchronous machine has had time to swing to a dangerous angle, beyond which recovery would be doubtful, is quick response. Or, considered from the standpoint of the fluxes in the synchronous machine, any excitation system that is quick enough to prevent a significant reduction in flux interlinkages due to demagnetizing armature current, as from a short circuit or other system disturbance, is quick response.

As a result of stability studies it has been established that a system will reach a critical point in its oscillation in something of the order of three-quarters of a second after the initiation of a disturbance, so that any corrective action, to be effective, must be made in less time than that. This requires a quicker exciter response than was used prior to the introduction, by us, of quick-response excitation. Previously exciters which were slow were speeded up to improve the voltage settling characteristics; that is, to restore the voltage to normal within a reasonable time; but not to any degree approaching the speed required to maintain stability.

The test data presented in the paper and similar data which we have obtained indicate that for certain applications considerable improvement in both steady static and transient limits result by increasing response of the exciter. However, in certain cases, the improvements in stability limits are extremely small and would not justify the increased cost and complication incurred. Quick response should not be considered as a panacea for all system stability troubles. In the present state of the art, each case for the application of quick response should be considered on its own merits.

J. H. Ashbaugh: The description of the exciter rheostatic regulator might give one the impression that this regulator is, if sensitive, always in a state of vibration. This is not true below the region of the static-state limit and I assume that Messrs. Nickle and Carothers did not intend to give this impression. The vibrating regulator will not maintain voltage much closer than 0.5 per cent due to imperfection of contacts. This imperfection of contacts is not present in the exciter rheostatic regulator so that it is just as sensitive as the vibrating regulator.

When transient stability is to be considered the exciter rheostatic regulator short circuits the exciter field rheostat the

same as a vibrating regulator, which is in my opinion all any regulator can do for the condition.

Another feature which I should like to emphasize is the anti-hunting device. The hunting associated with the type *D* regulator is probably due to improper adjustment rather than the particular form of anti-hunting device as evidenced by tests. Messrs. Nickle and Carothers state that "The proper time-phase relations are obtained largely by the mechanical design of the regulator and the use of anti-hunting devices as have been used in the past." I am somewhat inclined to this point of view and believe that the particular anti-hunting device used in this new regulator is but one of several that would be found satisfactory.

From tests which I have conducted I do not believe that the results with the type *D* regulator as outlined in Mr. Doherty's paper are representative of this regulator. It has been my experience that greater gains than shown were obtained with an increase in volts per second of the exciter. There are several features of importance with regard to adjustment of this regulator. These have an important bearing when steady-state limit as well as transients are considered.

C. A. Adams: The substance of the discussion thus far is to the effect that other regulators are just as satisfactory for the control of transient instability and that there is no need of control for continuous instability, owing to the fact that synchronous machines are not continuously operated in the unstable zone.

Concerning the operation of other regulators under conditions of transient instability, I cannot speak with authority, but I do know that this particular regulator does operate and is operating to protect against transient instability.

I cannot agree with the opinion that nothing is to be gained by a regulator which will enable synchronous machines to operate continuously in or near to the unstable zone and for the following reasons:

In the early days when alternators were practically all of the low-speed multipolar type, very close inherent regulation was specified; so close, in fact, that the armature short-circuit ratio was often as high as from 3-to-5, or even 6. Moreover, with the type of machine then prevalent, this high short-circuit ratio did not constitute any considerable handicap to the designer. However, the whole situation was changed with the advent of

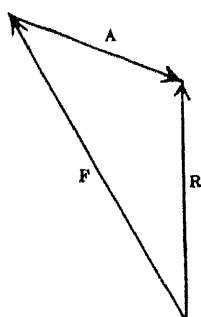


FIG. 1

the high-speed turbo alternator, where the limit of capacity is determined by the maximum allowable peripheral current density on the rotor. This point will be more readily appreciated from the vector diagram, Fig. 1 herewith. This is a simplified magnetomotive force diagram where *F* represents the field magnetomotive force, *A* the equivalent armature magnetomotive force proportional to the armature current, and *R* the resultant or reluctance magnetomotive force sufficient to produce a flux, the cutting of which by the armature conductors will generate the terminal voltage, ohmic drop in the armature being neglected.

The short-circuit ratio is approximately equal to R/A . For a given machine *F* is a measure of the peripheral current density (ampere-conductors per inch of periphery) on the rotor, and *A* of the peripheral current density on the stator.

Owing to tooth contraction on the rotor and to the requirements of mechanical strength of the teeth, the space available for copper per inch of periphery is absolutely limited, and hence the peripheral current density of the rotor. This is not the case on the stator, as there is no practical limit to the slot depth.

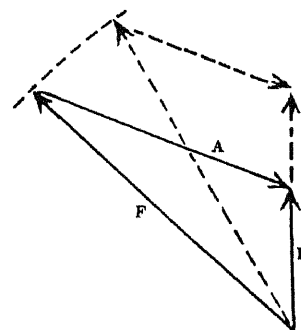


FIG. 2

Thus the real limit to the peripheral current density on the stator is the peripheral current density on the rotor and the maximum allowable ratio between the two; that is, between *A* and *F* in the diagram. The larger this ratio with the limiting value of *F*, the higher will be the possible rating and capacity of a machine of given air-gap dimensions; or, to put it in another way, for a smaller armature short-circuit ratio, which means a lesser inherent stability, the armature peripheral current density and *A* in the diagram can be larger for the same limiting value of *F*. This is shown in Fig. 2, herewith, in which Fig. 1 is reproduced in dotted lines and the diagram for the new machine of higher rating is shown in solid lines. *F* is the same for both of these machines. *A* is considerably larger for the new machine with the lower short-circuit ratio and the lesser inherent stability. *R* has been reduced, which simply means a shorter air-gap.

It is thus possible to increase the output of turbo generators with given length and rotor diameter, by shortening the air-gap and increasing the peripheral current density and copper on the armature.

The only reason why this has not been done before is because the resulting reduction in inherent stability was looked upon as dangerous. If, however, reliable regulators can be provided which will eliminate the danger from the reduction of inherent stability, I can see no reason why a considerable increase in capacity cannot be obtained at very small cost.

Therefore, a regulator which will accomplish this result certainly constitutes a real advance in the art of power generation and transmission.

R. H. Park: One of the most interesting results shown in the papers is the large difference between the operation of the new regulator, and the operation of the regulator without d-c. coil. Thus the data show that under steady load conditions the maximum power which could be carried, under the test conditions, was as follows:

New regulator.....	415 kw.
Regulator without d-c. coil.....	225 kw.

Subsequent tests with different adjustments indicated improved operation of the latter regulator. The results of these tests were as follows:

(A) Dynamic limit, steady load, two machines tied directly together.

Maximum power
transient possible
with stability

New regulator [*]	415 kw.
Regulator without d-c. coil (best adjustment).....	259 kw.
Hand control (fixed excitation).....	110 kw.

(The exciter speed used in connection with tests was approximately 250 volts per sec. It was found that increasing the speed of excitation did not improve the operation.)

(B) Same as (A) except shunt load of 124 kv-a. at 0.124 power factor.

Maximum motor
load possible with
stability

New regulator.....	461 kw.
Regulator without d-c. coil (best adjustment)....	317 kw.
Hand control (fixed excitation).....	173 kw.

(C) Same as (A) but machine separated by model 250-mile line.

Maximum motor
power possible
with stability

New regulator.....	105 kw.
Regulator without d-c. coil.....	98 kw.
Hand control (fixed excitation).....	67 kw.

(D) Same as (C) but shunt load of 62-kv-a. at 0.12 power factor at motor end.

Maximum motor
power possible
with stability

New regulator.....	88 kw.
Regulator without d-c. coil.....	82 kw.
Hand control (fixed excitation).....	57 1/2 kw.

(E) Same as (A) but machines separated by a 500-mile line:

Maximum power
possible with sta-
bility

New regulator.....	59 kw.
Regulator without d-c. coil.....	59 kw.
Hand control (fixed excitation).....	43 kw.

(F) Different machines separated by a reactance equal to 52 per cent of machine synchronous reactance, dynamic limit steady load.

Maximum power
possible with sta-
bility

New regulator.....	63 kw.
New regulator with two torque motors instead of one torque motor and one a-c. coil.....	63 kw.
Regulator without d-c. coil.....	51 kw.
Hand control (fixed excitation).....	38 kw.

The result of these tests is to confirm definitely the fact of an essential difference in operation between the two regulators; that is, to confirm one of the general theses of the papers that the new regulator in general possesses special characteristics particularly fitting it for controlling the operation of synchronous machines under conditions where dynamic stability is at a premium. This difference, however, as well as the gain which the regulator makes possible over hand control, diminishes as the length of line increases. The variation of dynamic limit of the two regulators, with length of intermediate line, is shown in

^{*}Same as described in paper except right-hand a-c. coil replaced by a torque motor.

Fig. 3 herewith. It will be seen from the figure that for lines of ordinary length the relative advantage of the new regulator is considerable.

After it is clear that there is a gain, it may be enquired whether these gains obtain in practise, or whether they apply to shop tests only. This point has not been completely explored yet. Experience has shown that the differential between the operation of the new regulator and the regulator without the d-c. coil decreases somewhat as the size of the machines tested increases. Therefore one difference which may be anticipated is that in the case of large machines this differential will be reduced.

Another difference is that in the tests made saturation was not present. Saturation, because it of itself tends to improve stability, reduces to some extent the gain which the regulator can accomplish.

Next it may be enquired where these gains in dynamic stability will be realizable. Of course, in most cases maximum power is not, as yet, felt as a limitation to normal operation. On the other hand, there are cases where the limitation of maximum power is encountered under normal conditions. These are in connection with power transmission over long lines, and in connection with power transmission over short lines where the power per circuit is very high. Of course, it is in just these cases that stability is of the greatest importance.

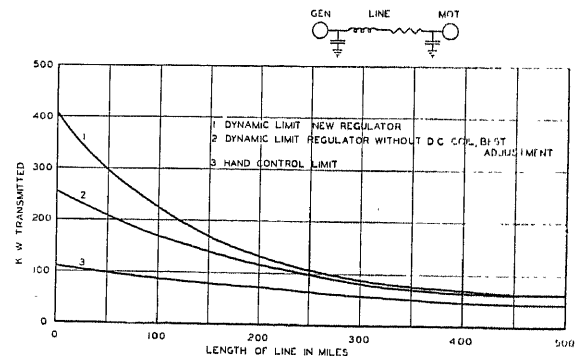


FIG. 3

Another instance is that of emergency conditions of operation. Thus, suppose a short circuit occurs and a line is dropped. In such a case it may be of great advantage to transmit a maximum of power over a weak tie line. In this case ability to operate in the zone of artificial stability should be of value.

A further consideration of very great importance is, how the regulator acts, during and after short circuits and sudden load changes. Thus, it might be supposed that the ability of the regulator to operate above the steady-state limit would disappear when short circuits and other disturbances are encountered. However, tests show that this is not the case. In general, the regulator is found to have two effects under transient conditions of operation, one an increase in the amount of power that can be carried with hand regulation, another a reduction in the tendency of machines to hunt. The amount of gain depends upon the severity of the short circuit or other disturbance. If the disturbance is slight, the gain is almost as great as that obtaining under steady conditions of operation. As the other extreme, a test in which 140 per cent resistance load is suddenly thrown onto two machines connected directly together, for a period of 0.6 sec., shows that the 230 per cent of the static limit can be carried with stability.

A test result is also available in an even more severe case. This case corresponds to a very severe short circuit on one of two parallel 250-mile lines. With the short circuit cleared at both ends in 0.6 sec., it was found that, with the new regulator, 108 per cent of the static limit of one line could be carried with stability.

Thus, the new regulator effects an improvement in stability, both under steady and transient conditions. As mentioned above, the gains under transient conditions are greater when the severity of the short circuit is less; if the short circuit is out in the middle of the line, it may be only half as severe, and consequently greater gains in stability due to the regulator are possible.

One other point of interest which may well be mentioned here is the fact that in general a somewhat different adjustment is required for best operation under transient conditions from that required under dynamic conditions. As shown by Nickle and Carothers in their paper, in the event of a short circuit or other disturbance involving a drop in machine terminal voltage the regulator acts to increase the exciter voltage in two steps, first by a sudden increase, in one vibration of the contacts, to an initial value; second, a process of continuous vibration according to which the terminal voltage is brought back to normal with a speed dependent on the degree of damping in the dashpot attached to the right hand lever. This process is illustrated in Fig. 4 herewith.

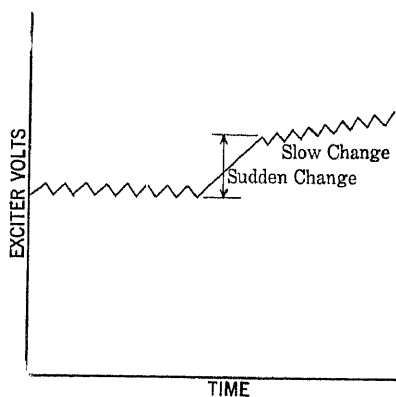


FIG. 4

The magnitude of the sudden change is freely adjustable through variation of the relative strengths of the d-c. and the a-c. elements on the left-hand lever, or, in the case of the type B regulator, by variation of the d-c. element and the stiffness of the spring in the spring dashpot.

From an analytical point of view, weakening the strength of the d-c. element relative to that of the a-c. element or the degree of elastance of the spring dashpot, corresponds to an increase in the negative resistance which the regulator inserts in the machine field. For best results under transient conditions the data at present available indicate that a low ratio of strengths of the d-c. and a-c. elements is desirable, thus corresponding to more than enough negative resistance in the machine field to compensate for its inherent positive resistance. (In general, the attainment of best all-around operation requires an adjustment involving some reduction in dynamic stability.) The exact adjustment to be employed in any particular case is variable depending on the severity and probable duration of the disturbances anticipated. The flexibility of the regulator by which it can be readily adjusted to meet any operating condition, is one of its most desirable characteristics.

C. A. Nickle: The discussions just presented seem to indicate that there is no serious disagreement with the main points brought out in this paper. With regard to the rheostatic type of regulator, its ability to regulate voltage under conditions of dynamic stability has been determined by test and we find that it does not seem suitable for this particular condition of operation. However, it is unquestionably satisfactory for operation below the static power limit and can satisfactorily take care of short circuits under this condition. It has been stated in the paper that this type of regulator has certain advantages not possessed by other types.

Mr. Powel has expressed the opinion that for transient conditions the only requirement of a regulator is that it close its contacts and keep them closed until the voltage is restored to approximately normal value. However, we do not believe that this is the only requirement for achieving the greatest stability under transient conditions. Sudden shocks, such as are imposed on a system by short circuits, necessarily result in system oscillations, and a regulator must be able to damp out such oscillations effectively. Otherwise, the system may break from synchronism, even after the exciting disturbance is over. The fact that a regulator closes its contacts promptly and keeps them closed until the voltage is approximately restored to normal, does not necessarily imply that the regulator has the proper anti-hunting characteristics.

R. E. Doherty: The most significant point about the discussion is that there appear to be no essential points of disagreement with what the authors consider to be the main contribution of the papers.

The foremost fact is that regulating means for increasing the maximum power of synchronous machines under conditions of dynamic stability have been much improved. Very substantial increases in maximum power above the steady-state limit, obtained by the use of the improved regulator, are given in the present papers. I do not find that anyone has questioned this fact.

To obtain such increases is an objective which has been actively sought during the last 4 or 5 years by engineers interested in power transmission. Credit is due to C. L. Fortescue for having apparently foreseen more clearly than any one else the possibility of attaining the objective by an improved regulator, and for predicting its development. Referring to tests which had demonstrated to him the *possibility* of operating in synchronism above the steady-state power limit by the use of an automatic voltage regulator (which I understand to be the a-c. coil type referred to by his associates in the present discussion), he made the following prediction at the Mid-Winter Convention in 1926:

"Now I am bringing out this point not to emphasize the point of difference, but because this artificial stability has an element of hope in it. If you can do it with a regulator today, you may be able to get a regulator that will do it still better tomorrow. You will surely be able to get more power over a given line tomorrow. Maybe the automatic regulator of special design will be the answer; maybe the inherent regulator scheme will be the answer. We don't know now, but one of these days we will know."

Such an automatic regulator of special design is now an accomplished fact, and the possible gains in maximum power by its use are promising in connection with the general development of power transmission.

Another noteworthy point on which there is practical agreement is the importance of operating through system disturbances—usually referred to under the heading of transient stability. It is agreed that this must be accomplished to the greatest practicable extent, whether the system is normally operated above the static limit or not.

Our tests show that the new regulator is efficacious in increasing the transient, as well as the dynamic, stability. In other words, it increases the power which can be carried through a system disturbance, as well as that which can be carried under steady load conditions. This is illustrated by the data which Mr. Park has given.

Thus, with reference to all of the foregoing, there appears to be no question raised in the discussion as to the results accomplished by the regulator. Nor do I find any adverse comment regarding the general theory as to how those results are accomplished—i. e., by the introduction of the effect of negative resistance⁵ in the field circuit by the use of the regulator. Thus as to

5. It is recognized that regulators using other principles of operation can also introduce negative resistance and thus increase stability limits.

the results and the theory which explains them, there seems to be no disagreement. And the authors regard these as the main contributions in the papers.

There are, however, some minor details which require explanation. Thus we are criticized, and perhaps justly, for not mentioning a test reported to have been made in 1925 in which the possibility of passing the steady-state limit was noted. However, the pertinent data regarding this test are not fully given in the literature, to our knowledge, and we know of no test since then which is comparable with those reported in the present papers. As to that one test, the conclusion drawn is freely acknowledged, namely, that it is possible to pass the steady-state limit by the use of the a-c. coil type of regulator.

As to other questions, Mr. Powel refers to the tests of Fig. 3 of my paper in which about four times the static power limit was obtained, with the statement that the ideal limit is infinity. This is merely a question as to what is taken as a standard of idealness. If the limit of the intermediate line is the standard Mr. Powel's figure is correct. However, we believe that a better standard is the degree to which the regulator compensates for armature reaction. On this basis the limiting power for comparison is that corresponding to transient reactance, and that limit is reasonably approached.

The advantage of the test with no intermediate line is that it shows the extent to which the regulator increases the capacity of the machines themselves, which is the object of the regulator. It is of course not intended that the regulator should neutralize the constants of the line. Calculations show that in practise the regulator compensates for about 95 per cent of armature reaction (*i. e.*, 95 per cent of $x_d - x_d'$).

At present it does not seem possible to overcompensate for armature reaction. Looking to the future, however, the perfection of the mercury arc rectifier and allied devices gives promise of affording improved regulating means embodying most of what appear to be the ideal regulating characteristics. With such a regulator, which would not involve vibrating contacts, it may be possible to overcompensate the armature reaction without inducing hunting.

As to "quick response," Mr. Evans questions my definition and proposes a new one. I hold no brief for the one I suggested. In the interest of accurate statement, I merely said what I meant by quick response. Now we have what Mr. Evans means by it. Any definition is all right which is generally accepted, or if not accepted, then accurately understood.

At the present writing sufficient data are not available to permit an exact statement of the best method of fulfilling excitation requirements in any given case. It would appear, however, that in many cases a moderate speed of response, say of the order of 200 volts per second on 250-volt fields, and half that much on 125-volt fields, would be sufficient. At the same time there are cases where somewhat higher speeds are desirable. Where conditions justify a maximum effort to obtain transient stability, the desirable arrangement would appear to be a combination of the new regulator and a stand-by super-excitation, the function of the latter being merely to "shoot" the excitation voltage to an appropriately high value during only the short interval of $\frac{1}{2}$ second or so, the balancing action of the new regulator then being resumed. Since the new regulator itself affords first-order gains in transient stability, the combination should afford additional gains and thus be justified.

Report of the Board of Directors

FOR THE FISCAL YEAR ENDING APRIL 30, 1928

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Forty-fourth Annual Report, for the fiscal year ending April 30, 1928. A general balance sheet showing the condition of the Institute's finances on April 30, 1928, together with other detailed financial statements, is included herein. The following is a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in the Institute JOURNAL.

Directors' Meetings.—The Board of Directors held seven meetings during the year, six in New York and one at Detroit, Michigan. The Executive Committee acted upon various matters during intervals between board meetings.

Information regarding the more important activities of the Institute which have been under consideration by the Board of Directors, the committees and the various officers, is published each month in the section of the JOURNAL devoted to "Institute and Related Activities."

President's Visits.—President Gherardi has attended three national and three regional conventions of the Institute during the past year and in addition has visited many of the Sections.

The following is a list of places visited: Detroit, Mich. (Summer Convention); Del Monte, Calif. (Pacific Coast Convention); New York, N. Y. (Winter Convention); Chicago, Ill. (Regional); St. Louis, Mo. (Regional); Baltimore, Md. (Regional); Regina, Can. (Saskatchewan Section); Vancouver, B. C.; Seattle, Wash.; Portland, Ore.; San Francisco, Calif.; Los Angeles, Calif.; Salt Lake City, Utah; Denver, Colo.; St. Louis, Mo.; Pittsburgh, Pa.; Ithaca, N. Y.; the president is scheduled to visit other Sections during May and the Annual Summer Convention in June.

Meetings.—Three national conventions of the Institute were held during the year, namely, the Summer, Pacific Coast, and Winter. The Annual Business Meeting was held in May. Regional meetings under the auspices of the Geographical Districts were held in Pittsfield, Mass., District No. 1; Chicago, Ill., District No. 5; St. Louis, Mo., District No. 7; Baltimore, Md., District No. 2.

Annual Meeting.—The Annual Business Meeting was held at Institute headquarters, New York, on May 20, 1927. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1927, was presented. The Tellers Committee made its report upon the election of officers for the administrative year beginning August 1, 1927.

Summer Convention.—The Forty-third Annual Summer Convention was held at Detroit, Michigan, June 20-24, 1927. Six technical sessions were held, at

which twenty-three papers and a symposium on television were presented. In addition, three other sessions were held, one being devoted to a lecture on "The Physical Nature of the Electric Arc" by Dr. K. T. Compton, and two to the presentation of fifteen technical committee reports. The Annual Conference of the Sections Committee was held on Monday, June 20; forty Sections were represented. The entertainment features included golf and tennis tournaments, a dinner, a boat trip, sightseeing, and special features. Numerous inspection trips were also made. About 1200 members and guests attended.

Pacific Coast Convention.—The Sixteenth Pacific Coast Convention was held at Del Monte, California, September 13-16, 1927. Four technical sessions and a general meeting were held, at which fifteen papers were presented and two addresses given. Attendance about 250.

Winter Convention.—The Sixteenth Winter Convention was held in New York, N. Y., February 13-17, 1928. At nine sessions twenty-nine technical papers were presented; a symposium on interconnection and its effect on power development (which included four papers and much discussion), a lecture, and a joint meeting with the Institution of Electrical Engineers by means of transatlantic telephony, were held. At another session the presentations of the John Fritz and Edison Medals took place. Numerous inspection trips, a smoker, and a dinner-dance were held. Attendance about 2000.

Regional Meetings.—Four regional meetings were held during the year:—the first in District No. 1 at Pittsfield, Mass., May 25-28, 1927, six technical sessions comprising forty papers were held, including one session devoted to the presentation of nine Student papers, attendance 550; second at Chicago, Ill., in District No. 5, November 28-30, four technical sessions were held, at which thirteen papers were presented, attendance 900; third at St. Louis, Mo., in District No. 7, March 7-9, 1928, four technical sessions were held at which fourteen papers were presented, attendance 500; fourth at Baltimore, Md., in District No. 2, April 17-20, four technical sessions were held, at which twelve papers were presented, attendance 400. In-

spection trips and social events were a part of each of these meetings.

The importance of the regional type of meeting has been further demonstrated during the year. The total attendance at the four regional meetings was 2350 and the total attendance at the three national conventions was 2930. This large attendance and the increased interest in the Institute throughout the country, which has developed as a result of the meetings, indicate that they are a very important part of the Institute's activities.

The regional committees which have had charge of these meetings are to be highly commended for their work. The success of the meetings has been due to their ability to plan, organize, and conduct the meetings.

Sections.—During the past year a large majority of the Sections has been very active. A considerable number of meetings has been devoted to general or moderately technical subjects of unusual interest with excellent results, and interest in purely technical meetings has been well-maintained. The success of the four regional meetings held during the year (see listing under Regional Meetings) furnishes additional evidence of Section activity.

The Columbus and Worcester Sections became members of the newly organized Affiliated Technical Societies of Columbus and Affiliated Engineering Societies of Worcester, respectively. About one-half of the Sections are now definitely affiliated in some manner with other local organizations.

At the 1927 Sections Committee Conference, progress was made in the development of means of bringing about closer relations between engineers and the general public, and an increased interest in the subject has become apparent. It was recommended that a combined report on Section and Branch activities be prepared annually beginning with the fiscal year ending April 30, 1928, and a general plan for the report has been approved by the Board of Directors.

Many Sections have continued to carry on very effective co-operation with neighboring Student Branches by sponsoring Student Conventions, having student programs at regular Section meetings, or holding joint meetings of other types with Branches.

Student Activities.—Almost all Branches have been active in holding local meetings, and there has been an increased interest in joint meetings and conventions.

During the year, effective Conferences on Student Activities were held in eight Geographical Districts, and both Counselors and Branch Chairmen have been enthusiastic concerning the benefits derived.

Eight very successful Student Conventions were held, four sponsored by Sections, and four by District Committees on Student Activities, and a considerable number of Branches participated.

Through the Conferences, Student Conventions, Section and Branch co-operation, the activities of the Counselors, and the Branch meetings, definite advances

have been made in the direction of bringing the students into closer contact with the Institute membership and better understanding of the opportunities for participation in its work.

Student activities have been reported more fully in the JOURNAL since the inauguration of the department for that purpose in January 1927. A revised edition of the "Suggested By-laws for Student Branches," approved by the Board of Directors, and a new pamphlet entitled "Student Activities" were printed.

New Branches were authorized at the University of Louisville and University of Vermont, and the Brown Engineering Society of Brown University became affiliated with the Institute under the provisions of Section 59A of the By-laws.

Section and Branch Statistics.—

	For Fiscal Year Ending			
	April 30 1921	April 30 1923	April 30 1925	April 30 1928
SECTIONS				
Number of Sections	42	46	49	52
Number of Section Meetings held	303	344	386	431
Total Attendance	37,823	46,672	49,029	64,276
BRANCHES				
Number of Branches	65	68	82	96
Number of Branch meetings held	443	503	548	915
Total Attendance	21,629	26,893	27,603	41,331

Meetings and Papers Committee.—The preparation of programs for national conventions and assistance with the programs of regional meetings constituted the principal work of the Meetings and Papers Committee during the year 1927-28. The committee members also, as part of their duty, reviewed miscellaneous papers submitted for publication and assisted the Prize Committee in preliminary selection of papers for prize awards.

The program for the Summer Convention, June 25-29, has been practically completed, and the schedule for the Pacific Coast Convention, August 28-31, has been tentatively arranged. The committee is also working on future meetings.

The total attendance at conventions and regional meetings was 5280, which is 800 above any previous year. The total number of papers presented was 159 including 15 annual reports of technical committees. Many noteworthy contributions to the literature in the various fields of electricity are contained in these papers.

One activity in connection with meetings on which considerable improvement has been made is the printing of advance copies of papers for distribution prior to the meetings. During the last year a much larger proportion of the papers has been printed in time for advance distribution. This improvement has resulted from special efforts exerted in three directions. First, the authors have been urged and persuaded to submit

their papers well in advance. Second, the reviewing committees have reduced their time of holding papers while reviewing them. Third, the Editorial Department has obtained closer cooperation with the printers and engravers, thus eliminating delays. Another factor which will undoubtedly assist in this matter is the separation of future meeting dates by at least six weeks, as recently approved by the Board of Directors on the recommendation of the Committee on Coordination of Institute Activities.

Publication Committee.—The Publication Committee has paid special attention to the form of Institute publications, resulting in the policy in force since January 1928. The constantly increasing volume of papers presented at Institute meetings each year made some change imperative, as under the former scheme of publication the limit of expense had been reached, and the size of the JOURNAL and TRANSACTIONS had become unwieldy.

The present scheme of publication, which has been described at length in recent issues of the JOURNAL, consists of advance pamphlet copies of complete papers, free to A. I. E. E. members on request; abridgments, not to exceed four pages, of all papers for the JOURNAL; complete papers with discussions in the QUARTERLY TRANSACTIONS.

Five issues of the JOURNAL have been published under the new plan and reports indicate that the abridgments make the JOURNAL a more readable paper than it formerly was for the membership in general; while the requests for complete pamphlet copies are numerous enough to show that this method of providing for the specialists is functioning satisfactorily.

The first number of the QUARTERLY TRANSACTIONS was published early in February and contained the papers for the last quarter of 1927. The second quarterly will be ready for distribution during May and will contain the papers and discussions of the 1928 Winter Convention, which, it should be noted, are thus made available for reference more than a year earlier than was possible with the annual publication plan.

The last volume of Annual TRANSACTIONS, No. XLVI, is completed and will be distributed in May. It includes the papers and discussion for 1927 from January to September and contains 1178 pages.

Law Committee.—During the year this committee has considered various proposed amendments to the Constitution of the Institute, the most important of these being for the purpose of authorizing a change in the date of the Annual Meeting from May to the Annual Summer Convention. This change was approved by the Board of Directors and was authorized at a Special Meeting of the Institute held in Chicago in November, 1927. The various amendments as finally approved by the Law Committee and the counsel of the Institute were submitted to the membership with a letter ballot under date of April 2, 1928.

Coordination Committee.—The Committee on Coordination of Institute Activities has considered and made recommendations to the Board of Directors upon various matters coming within its jurisdiction under the By-laws.

These matters have included consideration and favorable report to the Board of Directors upon the recommendations made at the conference of officers and Section delegates at the Summer Convention held in Detroit, in June 1927; the overlapping of committee work; the formulation and recommendation to the Directors of a policy regarding the coordination of future national and regional meetings; and the preparation and recommendation, after requesting and receiving the suggestions of District and Section officers, of a schedule of dates and locations of meetings up to the close of 1929. The latter recommendations are fully covered in a report made to the Board of Directors under date of April 3, 1928 and approved by the Board on April 6, as published in full in the May issue of the Institute JOURNAL.

Standards.—The Standards Committee has continued actively the revision of existing standards and the preparation of new standards. By new standards are meant standards for types of apparatus and equipment not covered in the 1922 complete edition of Institute Standards. Twenty-six separate sections have been approved by the Board as Institute Standards. Three sections are still in so-called report form, that is, they are available for comment and criticism by the membership of the Institute before final action by the Standards Committee and recommendation to the Board. Eight of the Standards have been approved as American Standard by the American Engineering Standards Committee, but all of the Standards, except those under actual revision, have been submitted for such approval.

At the request of the Board, the Standards Committee has made recommendations for representatives of the Institute on Sectional Committees. The Institute is sole sponsor for six projects, joint sponsor for 15, and has representation on 29 other Sectional Committees under A. E. S. C. procedure. The Standards Committee receives reports from these representatives and makes recommendations to the Board based on such reports.

Spanish translations of eight standards were published by the Bureau of Foreign and Domestic Commerce, Department of Commerce, Washington, D. C., during the year. A folder in English and Spanish, listing all the standards available in the Spanish language, was prepared and widely circulated in the Spanish-speaking countries of South and Central America. Arrangements are also being made with the Bureau of Foreign and Domestic Commerce to make revisions in the Spanish text, when standards are revised.

The committee has continued very close cooperation with the United States National Committee of the

International Electrotechnical Commission. Of the 22 delegates to the Bellagio, Italy, meeting of the Commission (Sept. 1927), 18 are members of the Institute. There has been the closest cooperation between groups of advisers, U. S. N. C., I. E. C., Sectional Committees, Technical Committees, and the Standards Committee.

Several important new projects have been initiated. The formation of a Sectional Committee on definitions in the electrical field, under the sponsorship of the Institute, has been recommended. It is very desirable that there be unification and coordination of definitions in the electrical art and industry. An important and far-reaching resolution, prepared by the Instruments and Measurements Committee, on the relation of the international electrical units to the fundamental absolute units was considered and its adoption recommended to the Board.

American Engineering Standards Committee.—

Aside from the routine matters on which the Institute delegates to American Engineering Standards Committee have been required to vote, covering such matters as the approval of standards, the delegation has attempted faithfully to serve the larger interests of American Engineering Standards Committee consistently with the policies of the Institute as laid down by the Board of Directors in the reviewing of the status of American Engineering Standards Committee and its readjustment to a changing national emphasis in the matter of standards.

The delegation has felt a primary responsibility in making clear to the other members that the American Institute of Electrical Engineers regards itself as being if not the principal at least one of the more significant influences in the inception of the work of formulating American Electrical Standards and procuring their recognition. It is believed that much has been accomplished in making clear that the American Institute of Electrical Engineers is in sympathy with the purposes and ideals of American Engineering Standards Committee. To this end the delegation has attempted to interpret the Institute to American Engineering Standards Committee and conversely to keep the Board of Directors advised of developments in American Engineering Standards Committee.

The latter organization has during the year, with the strong support of the Institute, entirely revised its methods of procedure in a manner which already has clarified and expedited the process of giving recognition to American standards and is at the present time actively concerned in the matter of a general re-constitution which shall bring the processes of standardization more nearly into coincidence with a changing condition which arises from the more general industrial recognition of the necessity for universally accepted national standards. The Institute representatives are, at the present time, taking an active part in the determination of the lines along which such re-constitution should proceed and it is believed will do so without any conflict

with the fundamental purposes of the American Institute of Electrical Engineers.

U. S. National Committee of I. E. C.—The work of the United States National Committee of the International Electrotechnical Commission for the past year was very largely centered in preparation for and participation in the Plenary Meeting of the commission which was held in Italy, September 1927. Because of the character of its organization and the large amount of very effective work which was done by the various groups of advisors cooperating with all branches of the industry, delegates of the U. S. National Committee went to the meeting in Bellagio well prepared to put forward the views of the industry in this country in all the various matters with which the commission is concerning itself.

The meetings at Bellagio covered the period from September 3 to 11, during which time the Advisory Committees convened and very substantial progress was made in the work of the commission. This work does not lend itself readily to description in a summarized way largely because it is in different states of completion.

On the occasion of a formal dinner the American delegates presented to the Italian National Committee a bust of Benjamin Franklin on behalf of all of the eighteen visiting nationalities. The presentation was received with words of warmest appreciation.

Following the meetings in Bellagio came a tour offered by the Railway Administration of Italy, and a Plenary Meeting in Rome.

The work of the committee has been actively resumed since the Bellagio Meeting and it is the expectation of the U. S. National Committee that by the time of the next Plenary Meeting of the commission, to be held in the Scandanavian countries in 1930, a large amount of material will be ready for final consideration.

U. S. National Committee of the International Commission on Illumination.—The International Commission on Illumination had been scheduled to hold a Plenary Meeting in the United States in the year 1927 but for various reasons it seemed best that this Plenary Meeting should be put off for a year and a series of committee meetings should be held in Europe. Technical Committees of the Commission as well as the Executive Committee were accordingly convened at Bellagio, Lake Como, on the 31st of August and meetings were held on that day and on the 1st and 2nd of September, 1927. At these meetings the U. S. National Committee was represented by the seven delegates.

Apart from the technical matters considered there was brought up the consideration of recommendations of the U. S. National Committee with respect to the scope of the work of the commission. As a result the scope of the commission's work was considerably enlarged so that at the present time there are some fifteen subjects being considered. The Secretariats for these subjects are distributed amongst the various

National Committees, thus distributing the work and throwing an undue burden on none.

The Secretariats assigned to the United States are as follows: Headlights; Factory and School Lighting.

The Executive Committee of the Commission voted to hold the next Plenary Meeting in America in September, 1928, and the U. S. National Committee has been engaged in preparations for this meeting. It seemed to the committee that it would be fitting to request the Illuminating Engineering Society to make the necessary arrangements for this meeting. Such a request was made and accepted and the preparations for the meeting have been coming on actively.

In view of the scope of the meeting, which exceeds somewhat that of previous I. C. I. meetings because of the desire to bring in representatives of nationalities not now represented on the I. C. I., the entire meeting has been designated as an International Illumination Congress.

Committee on Safety Codes.—Probably the most important action taken by the committee has been the approval of the set of Standard Rules for the application of the Prone Pressure Method of Resuscitation, which was prepared for universal adoption in this country under the auspices of the United States Public Health Service, with many other organizations cooperating.

The committee also further gave its approval to the Manual of Standard Practice as prepared and approved by the American Gas Association and National Electric Light Association, which includes the rules named above.

The committee is continuing its work in endeavoring to get proper safety activities developed in the Sections and Branches. This work includes the appointment of suitable liaison officers from the National Safety Council; arrangements for cooperation with other bodies in local, community safety meetings.

The work of the Branches naturally is confined largely to suitable activities in the Branches themselves. It is the intent to direct these activities so that the graduating classes will be more fully aware of their responsibilities for accident prevention, and more fully trained in the use of tried safety methods than has been often the case in the past.

Finally, the committee has taken action recommending to the Board of Directors that the Institute offer its support to the National Safety Council in carrying through the Annual Safety Congress for 1928, which is to be held in New York City next October.

Technical Committees.—Reports of Technical Committees embracing an outline of the year's work and a summary of progress in the industry will be presented at the Annual Summer Convention and printed in the TRANSACTIONS.

Membership.—The following table gives the number of members added to the roll during the year and the number whose affiliations have terminated through resignation, death, or delinquency in dues. The

membership total as of May 1, 1928, is 18,265. The slight decrease in total membership, as shown, is due to special causes of a temporary nature, which operated during the year.

	Honorary	Fellow	Member	Associate	Total
Membership on April 30, 1927..	4	644	2,931	14,770	18,349
Additions:					
Transferred		26	255		
New Members					
Qualified.....		1	77	1,503	
Reinstated.....		1	12	81	
Total.....	4	672	3,275	16,354	20,305
Deductions:					
Died		8	20	48	
Resigned		4	26	440	
Transferred.....			17	264	
Dropped		1	48	1,164	
Membership April 30, 1928 ...	4	659	3,164	14,438	18,265

Deaths.—The following deaths have occurred during the year.

Fellows: James R. Craighead, Elmer E. F. Creighton, William C. L. Eglin, Alexander C. Humphreys, James Kynoch, Paul Spencer, Charles Vernier, James J. Wood.

Members: Frederick L. Baer, James E. Barker, Louis C. Brooks, Aubrey L. Broomall, Harry L. Brown, Blanchard C. Edgar, Carlo Ferrari, Frank E. Field, James M. Graves, George Ross Green, Charles T. Guildford, Harry E. Hayes, George L. Hedges, Augustus T. Holbrook, Robert M. Lloyd, Allen H. Moore, Michael C. Polivanoff, Ernest E. Schmid, Irving W. Smith, Hugh T. Wreakes,

Associates: Jean B. Balcomb, William K. Benz, Ole S. Beagstad, Abel L. Brownrigg, Charles F. Brush, Jr., George A. Buchanan, William C. Chappell, Henry H. Curtis, R. T. Davis, Charles S. Dawson, Charles P. Drake, George Eisenhauer, Charles H. Fisher, Sydney Fisher, Maurice C. Fitzgerald, George H. Gettess, William F. M. Goss, Baxter R. Grier, Edmund M. Hallowell, James W. Harris, Alexander W. Hearne, Harry G. Hopkins, Roy D. Huxley, Frank E. Idell, Johannes Johansen, Senter M. Jones, Paul T. Kamerer, Keijiro Kishi, Arthur R. Leavitt, Basil W. Lee, Archie L. Lewis, Gordon E. McLean, Robert Miller, Otis Sherman Newton, Frederick E. Norman, Ralph M. Obergfell, John L. Phillips, William E. Poole, Fred B. Seem, Frederick G. Simpson, Walter Stumpf, Soichi Takeda, Frank F. Thompson, Howard F. Thurber, Beverley B. Tucker, Thomas A. Wilkinson, Harold P. Williamson, Byron M. Wood.

Board of Examiners.—The Examiners have had before them during the past year the question of the comparative number of members of the Institute in the three grades of Associate, Member, and Fellow, and whether the present number in those grades represented a true cross-section of the electrical field with regard to the professional accomplishments of the

members and the positions held. A special committee has been authorized by the Directors to consider this entire question. The total number of cases of admission and transfer considered by the Examiners this year is indicated below:

APPLICATIONS FOR ADMISSION

Recommended for grade of Associate.....	1243	
Not recommended.....	13	1256
<hr/>		
Recommended for grade of Member.....	78	
Not recommended for admission to this grade.....	25	103
<hr/>		
Recommended for grade of Fellow.....	2	
Not recommended for admission to this grade.....	1	3
<hr/>		
Recommended for enrolment as Students..		1967

APPLICATIONS FOR TRANSFER

Recommended for grade of Member.....	280	
Not recommended for transfer to this grade	17	297
<hr/>		
Recommended for grade of Fellow.....	21	
Not recommended for transfer to this grade	3	24
<hr/>		
Total number of applications considered...		3650

Institute Prizes.—At the meeting of the Board of Directors of the Institute of June 23, 1927, recommendations of the Committee on Award of Prizes were approved establishing five National prizes of \$100.00 cash and suitable certificates to be awarded yearly as follows: Three First Prizes for (a) Engineering Practise, (b) Theory and Research, (c) Public Relations and Education; and in addition a Prize for Initial Paper and Prize for Branch Paper. The following Regional prizes may also be awarded yearly in each of the ten Geographical Districts, each prize to consist of \$25 and suitable certificate, as follows: First Prize, Prize for Initial Paper, Prize for Branch Paper.

The awards for the year 1927 have not as yet been made but the committee's report is expected in May. The presentations will take place at the Denver meeting.

Scholarships.—The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute committee. The scholarships pay \$350 toward annual tuition with provision for reappointment. An award for the academic year 1927-28 was made to Walter L. Lawrence.

Complete details governing prizes and scholarships may be obtained by applying to the National Secretary of the Institute.

Edison Medal.—The Edison Medal, founded by

associates and friends of Thomas A. Edison, is awarded annually by a committee consisting of twenty-four members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1927 was awarded to William D. Coolidge, "for his contributions to the incandescent electric lighting and the X-ray arts." The presentation took place at the Winter Convention of the Institute, February 15, 1928.

John Fritz Medal.—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of Civil, Mining, Mechanical, and Electrical Engineers, awarded the twenty-fourth medal to John J. Carty, of New York, "for achievements in telephone engineering." The medal was presented at New York at the Winter Convention of the Institute, February 15, 1928.

Lamme Gold Medal.—A bequest was made by the late B. G. Lamme, to cover the cost of an annual award by the Institute of a gold medal, to a member who has shown meritorious achievement in the development of electrical apparatus. The conditions governing the award of the Lamme Gold Medal are now being prepared by a special committee.

Commission of Washington Award.—The Washington Award for 1928 was made to Dr. Michael I. Pupin "for devotion to scientific research leading to his inventions which have materially aided the development of long distance telephony and radio-broadcasting."

The award is made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of nine representatives of the Western Society of Engineers and two each from the A. S. C. E., the A. I. M. E., the A. S. M. E., and the A. I. E. E.

Employment Service.—The employment service which the Institute has maintained for many years is conducted as a cooperative bureau in conjunction with a similar service maintained by the National Societies of Civil, Mining, and Mechanical Engineers under the title, "Engineering Societies Employment Service." In addition to the main office in the Engineering Societies Building, New York, offices have been opened in Chicago in cooperation with the Western Society of Engineers and in San Francisco under similar arrangements with the California Section, American Chemical Society, and Engineers Club of San Francisco. Arrangements have been completed to open a branch office in Denver, Colorado, in cooperation with the Colorado Engineering Society. It is hoped to continue this development from year to year as conditions warrant. The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the "Employment Service Bulletin" in the

monthly JOURNALS, weekly subscription bulletins are issued for those seeking positions.

American Engineering Council.—American Engineering Council, with which the Institute is affiliated, is completing its eighth year as representative of its constituents, at conferences, conventions, on important committees of other organizations, and at Congressional hearings. It now has a membership of 25 national, state, and local engineering societies totalling an individual membership of something over 43,000 professional engineers.

During the past year it has extended aid of a valuable character to over 200 societies and individuals. Council is becoming well known as an authoritative source of information and reference.

Council, however, does not confine itself to such activities but pursues many other projects. It has representatives on such government committees as the Advisory Council to the Board of Surveys and Maps, the Planning Committee of the Division of Simplified Practice, the Committee appointed to draft a Uniform State Mechanics Lien Act, and the several executive committees of the Hoover Conference on Street and Highway Safety. It likewise has representatives on committees formed by other groups, as the U. S. Chamber of Commerce, the National Bureau of Economic Research, the World Congress of Engineers, and the celebration of the 200th anniversary of the birth of George Washington.

The legislative year has been an exceedingly busy and active one.

The Public Affairs Committee is completing the busiest year of its existence. Never before since the establishment of Council have so many bills been introduced into a single session of Congress which have come so directly within the purview of American Engineering Council.

Council has continued its active support of and is hopeful that most of the following measures will be passed during this session of Congress: Newton Bill, calling for an inventory of the water resources of the United States; Parker Bill, providing an equitable status for sanitary engineering and sanitary engineers in the U. S. Public Health Service; Wyant Bill, which assembles the greater part of the civil engineering and construction services of the Government under one government division in the Department of the Interior; Ransdell Bill, which calls for the establishment of a national hydraulic laboratory in the U. S. Bureau of Standards; and the McNary-Woodruff and McNary-McSweeney Bills which provide for a fixed national forestry policy and for an augmented research program by the Department of Agriculture in certain matters pertaining to forestry.

The Council has continued its opposition to the Swing-Johnson Bill; to legislation seeking to grant certain patents to Garabed K. Giragossian, without jurisdiction of the Patent Office; to Government

ownership and operation of certain projects, as Muscle Shoals; to any legislation which tends to nullify the Federal Power Commission's jurisdiction.

The year has seen the completion of two studies: Safety and Production; and Street Signs, Signals, and Markings. Safety and Production is now off the press and being distributed. The report on Street Signs, Signals, and Markings will be issued in pamphlet form within the next few months. It is expected that the recommendations of the Committee on Street Signs, Signals, and Markings will be adopted as American standard. Legislative activity is now under way which will culminate in the adoption, almost in toto, of the recommendations of Council's Committee as state requirements by the State Legislatures of New York and of New Jersey.

Important special committees which will function throughout the year are Flood Control, Radio Broadcasting, President's Committee on Constitution, By-Laws and Activities of American Engineering Council, Patents, Power, and Program of Research.

The Flood Control Committee has been and will continue to be active in connection with the Mississippi Valley flood problems; the Radio Broadcasting Committee is continuing to render valuable assistance to the Federal Radio Commission; the Patents and Power Committees have been active in connection with numerous pieces of legislation, both desirable and undesirable, which have been before Congress for consideration. The Program of Research Committee is undertaking to establish certain fundamental principles which shall govern future research policies of American Engineering Council.

United Engineering Society.—This Society performs for the national societies of Civil, Mining, Mechanical, and Electrical Engineers, certain specific acts which are governed by contracts; the primary function of the United Society being to hold in trust and to administer for these societies the Engineering Societies Building, in which the headquarters of the national societies are located.

Extracts from the annual financial report of the United Engineering Society were published in the March 1928 JOURNAL.

Engineering Societies Library.—The library of the Institute is combined with the libraries of the national societies of Civil, Mining, and Mechanical Engineers, administered as the "Engineering Societies Library" under the direction of the Library Board of the United Engineering Society; this board is composed of representatives of each of the four societies referred to above.

In order to place the facilities of the library at the disposal of persons residing at a distance from New York, a Library Service Bureau has been established, and a staff of expert searchers and translators is employed to cover almost any engineering topic, in the following manner: abstracting, translating, bibliographing, statistical searches and reports, searches

for patent purposes, copying, preparing reference cards, etc. A lending department is also maintained.

A copy of the annual report of the Engineering Societies Library covering the calendar year 1927, may be obtained by applying to Institute headquarters.

Engineering Foundation.—Engineering Foundation is a trust fund established in 1914 by Ambrose Swasey, of Cleveland, Ohio, by gifts to United Engineering Society as a nucleus of a large endowment “for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind.” The fund has been generously increased through the gifts of Edward D. Adams and others, and also through bequest under the will of the late Henry R. Towne. It is administered by the Engineering Foundation Board upon which the Institute and other national engineering societies are represented. The Board is a Department of United Engineering Society.

The Foundation has made appropriations for various research projects and has cooperated in others.

The annual report of the Foundation is available in printed form.

Representatives.—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years, and has accepted sponsorship and appointed representatives upon a number of new Sectional Committees of American Engineering Standards Committee. A complete list of representatives is published frequently in the JOURNAL.

Finance Committee.—During the year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws.

Haskins and Sells, certified public accountants, have audited the books, and their report follows:

Respectfully submitted for the Board of Directors

F. L. HUTCHINSON,

New York, May 18, 1928

National Secretary.

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS

OFFICES IN THE PRINCIPAL CITIES OF
THE UNITED STATES OF AMERICA
—AND IN—
LONDON, PARIS, BERLIN, SHANGHAI,
MONTREAL, HAVANA, MEXICO CITY

37 WEST 39TH STREET
NEW YORK

May 17, 1928.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have made a general audit of your accounts for the year ended April 30, 1928, and submit the following exhibits and schedule:

Exhibit

A—Balance Sheet, April 30, 1928.

Schedule 1—Reserve Capital Fund—Securities.

B—Summary of Income and Profit and Loss for the Year Ended April 30, 1928.

WE HEREBY CERTIFY that in our opinion Exhibits A and B, respectively, correctly set forth the financial condition of the Institute at April 30, 1928, and the results of its operations for the year ended that date.

Yours truly,

HASKINS & SELLS

EXHIBIT A.

BALANCE SHEET, APRIL 30, 1928

ASSETS			LIABILITIES	
REAL ESTATE:			CURRENT LIABILITIES:	
One-fourth interest in United Engineering Society's Land, Building, and Building Equipment, 25 to 33 West 39th Street (Depreciation carried on books of United Engineering Society)		\$493,352.60	Accounts Payable.....	\$ 14,182.09
EQUIPMENT:			Dues Received in Advance.....	2,772 07
Library—Volumes and Fixtures.....	\$ 41,298.96		Entrance Fees and Dues Advanced by Applicants for Membership.....	556.85
Works of Art, Paintings, etc.....	3,001.35		Subscriptions for "Transactions" Received in Advance.....	79.00
Office Furniture and Fixtures.....	\$27,037.87		Total Current Liabilities	\$ 17,590.01
Less Reserve for Depreciation (including \$5,884.29 funded).....	10,316.68	16,721.19	FUND RESERVES (NOT INCLUDING DEPRECIATION RESERVES):	
Total Equipment.....		61,021.50	Reserve Capital Fund.....	\$143,711 88
WORKING ASSETS:			Life Membership Fund.....	11,340.64
"Transactions," etc.....	\$ 4,490.75		International Electrical Congress of St. Louis—Library Fund.....	4,141 01
Paper and Cover Paper.....	5,245.94		Mailloux Fund.....	1,025.00
Badges.....	2,181.12		Lamme Medal Fund.....	5,321.83
Total Working Assets.....		11,917.81	Total Fund Reserves (Not Including Depreciation Reserves).....	165,543.39
CURRENT ASSETS:			SURPLUS, Per Exhibit "B".....	\$599,172.69
Cash.....	\$ 12,551 96			
Accounts Receivable:				
Members—For Dues.....	23,735.68			
Advertisers.....	1,147.00			
Miscellaneous.....	5,457.33			
Accrued Interest on Investments.....	1,994.53			
Total Current Assets.....		44,886.50		
FUNDS:				
Reserve Capital Fund:				
Securities—Schedule 1.....	\$143,711 88			
Life Membership Fund:				
Cash.....	\$ 6,438.56			
Chicago, Burlington & Quincy Railroad Company 4% Bonds, 1958, Registered, Par Value \$5,000.00.....	4,868.75			
Accrued Interest.....	33.33	11,340.64		
International Electrical Congress of St. Louis—Library Fund:				
Cash.....	\$ 990.74			
New York City 4½% Corporate Stock, 1957, Par Value \$2,000.00.....	2,204 05			
New York Telephone Company 4½% Bond, 1939, Registered, Par Value \$1,000.00.....	878.75			
Accrued Interest.....	67.50	4,141.04		
Mailloux Fund:				
Cash.....	\$ 2.50			
New York Telephone Company 4½% Bond, 1939, Registered, Par Value, \$1,000.00.....	1,000.00			
Accrued Interest.....	22.50	1,025.00		
Lamme Medal Fund:				
Cash.....	\$ 894.83			
Baltimore and Ohio Railroad Company 6% Refunding and General Mortgage Series "C" Bond, 1995, Par Value \$4,000.00.....	4,330.00			
Accrued Interest.....	100.00	5,324.83		
Depreciation of Furniture and Fixtures Fund:				
Cash.....	\$ 871.79			
Cleveland Union Terminals Company 5% Sinking Fund Series "B" Gold Bonds, 1973, Registered, Par Value \$5,000.00.....	5,012.50	5,884 29		
Total Funds.....		171,427.68		
Total.....		\$782,606.09	Total.....	\$782,606.09

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

SUMMARY OF INCOME AND PROFIT AND LOSS FOR THE YEAR ENDED APRIL 30, 1928

EXHIBIT B.

INCOME:

Dues.....	*\$227,666.66	
Students' Fees.....	10,917.00	
Entrance Fees.....	15,525.00	
Transfer Fees.....	1,460.00	
Advertising.....	82,978.19	
Journal Subscriptions.....	10,164.38	
"Transactions" Subscriptions.....	19,503.19	
Miscellaneous Sales.....	10,126.09	
Badges Sold.....	\$ 4,290.65	
Less Cost.....	3,505.08	785.57
Interest on Securities in Reserve Fund.....	6,874.20	
Interest on Bank Balances.....	1,220.69	
Total.....		\$387,220.97

EXPENSES:

Publications:		
Journal.....	\$103,497.42	
"Transactions".....	31,250.50	
Year Book.....	7,626.27	
Miscellaneous.....	3,778.94	\$146,153.13
Institute Meetings.....	25,953.90	
Administrative Expenses.....	59,864.70	
Sections.....	31,119.94	
Membership.....	7,454.69	
Standards.....	8,103.92	
Finance.....	350.00	
Headquarters.....	1,507.70	
Code Committee.....	60.00	
Technical Committees.....	192.45	
Edison Medal.....	308.10	
Law Committee (Revision of Constitution).....	1,019.39	
Geographical Districts Expense:		
Traveling expense:		
Executive Committee.....	\$ 1,523.69	
Vice-Presidents.....	973.99	
Speaker's Bureau.....	64.26	
Best Paper Prize.....	100.00	
First Paper Prize.....	75.00	2,736.94
Branch Activities:		
Meetings.....	\$ 537.26	
Traveling Expense—Counsellors.....	5,286.33	
Salaries and Miscellaneous.....	2,435.65	8,259.24

Forward..... \$293,084.10 \$387,220.97

TOTAL INCOME—FORWARD..... \$387,220.97

EXPENSES—(FORWARD)..... \$293,084.10

American Engineering Standards Committee.....	1,500.00	
International Electrotechnical Commission.....	1,521.16	
United States National Committee of International Commission on Illumination.....	300.00	
Louvain Memorial.....	929.27	
President's Special Appropriation.....	357.24	
Board of Directors—Traveling Expenses.....	3,668.46	
National Nominating Committee, Traveling Expenses.....	979.03	
Institute Representatives—Traveling Expenses.....	178.27	
Honorary Secretary.....	4,000.00	
John Fritz Medal.....	417.53	
Engineering Societies Library—Maintenance.....	8,729.14	
United Engineering Society Assessment.....	5,711.04	
American Engineering Council.....	17,725.00	
Engineering Societies Employment Service.....	1,635.00	
International Annual Tables.....	100.00	
Institute Prizes.....	400.00	

Total..... 341,235.24

NET INCOME..... \$ 45,985.73

PROFIT AND LOSS CREDITS:

Adjustment of Inventories:		
"Transactions".....	\$ 669.25	
Library Volumes and Fixtures.....	691.12	1,360.37

GROSS SURPLUS FOR THE YEAR..... \$ 47,346.10

PROFIT AND LOSS CHARGES:

Uncollectible Dues and Members' Charges Written Off.....	\$ 12,110.35	
Furniture, Fittings and Equipment Scrapped or Sold—Net.....	117.23	
Provision for Depreciation of Furniture and Fixtures.....	1,343.66	

Total..... 13,571.24

SURPLUS FOR THE YEAR..... \$ 33,774.86

SURPLUS, MAY 1, 1927..... \$602,756.01

†Less Transferred to Capital Fund Reserve in Accordance with Resolution of the Board of Directors.....	37,058.18	565,697.83
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SURPLUS, APRIL 30, 1928..... \$599,472.69

*Includes \$103,724.00 allocated to subscriptions for the JOURNAL and TRANSACTIONS.

†Includes authorized investments for appropriation year beginning October 1, 1926 and part of authorized investments for ensuing year.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

RESERVE CAPITAL FUND—SECURITIES

APRIL 30, 1928

EXHIBIT A.

SCHEDULE No. 1.

	Par Value	Book Value		Par Value	Book Value
RAILROAD BONDS:			PUBLIC UTILITY BONDS:		
Baltimore and Ohio Railroad Company 4½% Convertible Gold Bonds, Due 1933, Registered.....	\$10,000.00	\$ 9,387.50	Consolidated Gas Company of New York 5½% Gold Debentures, Due 1945, Registered.....	\$5,000.00	\$ 4,187.50
Baltimore and Ohio Railroad Company 6% Refunding and General Mortgage Series "C" Bonds, Due 1995, Registered.....	8,000.00	8,940.00	Duquesne Light Company 4½% First Mortgage Series "A" Gold Bonds, Due 1967, Registered.....	3,000.00	2,970.00
Central of Georgia Railway Company 5½% Refunding and General Mortgage Bonds, Due 1959, Registered.....	5,000.00	5,283.75	Pacific Gas & Electric Company 5½% First and Refunding Mortgage Gold Bonds, Due 1952, Registered.....	5,000.00	4,137.50
Chicago and Erie Railroad Company 5% First Mortgage Gold Bonds, Due 1982, Registered.....	1,000.00	1,105.00	The American Telephone and Telegraph Company 5% Gold Debentures Sinking Fund, Due 1960, Registered.....	15,000.00	14,650.00
Chicago, Burlington & Quincy Railroad Company 5% First and Refunding Mortgage Series "A" Gold Bond, Due 1971, Registered.....	1,000.00	1,010.00	The Detroit Edison Company 6% First and Refunding Mortgage Series "B" Gold Bonds, Due 1949, Registered.....	5,000.00	4,187.50
Chicago, Terre Haute & Southeastern Railroad Company 5% First and Refunding Mortgage Gold Bonds, Due 1960.....	8,000.00	7,940.00	Total.....	\$43,000.00	\$ 39,082.50
Florida East Coast Railway Company 5% First and Refunding Mortgage Series "A" Gold Bonds, Due 1974, Registered.....	10,000.00	9,818.75	INDUSTRIAL BONDS		
Great Northern Railroad Company 5½% General Mortgage Series "B" Gold Bonds, Due 1952, Registered.....	10,000.00	9,847.50	American Smelting and Refining Company 5% First Mortgage 30-Year Gold Bonds, Due 1947, Registered.....	\$5,000.00	\$4,087.50
St. Louis, San Francisco Railway Company 5% Prior Lien Mortgage Series "B" Bonds, Due 1950, Registered.....	6,000.00	5,497.50	American Smelting and Refining Company 6% First Mortgage Bonds, Due 1947.....	5,000.00	4,087.50
Southern Railway Company 5% First Consolidated Mortgage Gold Bonds, Due 1994, Registered.....	1,000.00	980.00	Bethlehem Steel Company 5% Purchase Money and Improvement Mortgage 20-Year Sinking Fund Gold Bonds, Due 1936, Registered.....	5,000.00	4,087.50
The New York Central Railroad Company 5% Refunding and Improvement Mortgage Series "C" Bonds, Due 2013, Registered.....	6,000.00	5,742.50	New York Steam Corporation 6% First Mortgage Gold Bonds, Due 1947, Registered.....	10,000.00	9,087.50
The Pennsylvania Railroad Company 4½% General Mortgage Series "A" Gold Bonds, Due 1965, Registered.....	5,000.00	5,130.00	The Western Electric Company 5% Bonds, Due 1944.....	10,000.00	9,087.50
Total.....	\$71,000.00	\$70,682.50	United States Rubber Company 5% First and Refunding Mortgage Series "A" Bonds, Due 1947.....	5,000.00	4,087.50
			Total.....	\$50,000.00	\$44,442.50
			Total.....	\$114,000.00	\$114,125.00

